CR 86167

TRW No. 09776-6009-R0-00

NAVIGATION/TRAFFIC CONTROL SATELLITE MISSION STUDY

VOLUME II
SYSTEM ANALYSES

CRAIGIE, DOBIESKI, RAYMOND, SCHULTZ, MITCHLER, ET AL.

JUNE 1969

Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Prepared under Contract No. NAS 12-595 by

TRW SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278

TRW No. 09778-6009-R0-00

NAVIGATION/TRAFFIC CONTROL SATELLITE MISSION STUDY

VOLUME II
SYSTEM ANALYSES

CRAIGIE, DOBIESKI, RAYMOND, SCHULTZ, MITCHLER, ET AL.

JUNE 1969

Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Prepared under Contract No. NAS 12-595 by

TRW
SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278

ACKNOWLEDGMENT

The Navigation/Traffic Control Satellite Mission Study has been an extensive team effort. While numerous technical personnel made contributions to the study, the following TRW Systems people made significant contributions to this volume:

Section 1	Introduction	J. H. Craigie, D. D. Otten
Section 2	Requirements and Criteria	J. H. Craigie
Section 3	Communications Load Analysis	S. Blum, A. W. Dobieski, T. Smuczynski, J. H. Craigie, L. Kleinrock
Section 4	Communications Subsystem Analysis	H. G. Raymond, A. Garabedian, A. Savino
Section 5	Position Determination Subsystem Analysis	P. R. Schultz, L. J. Mitchler W. G. Meyers, W. M. Holmes, J. C. McMunn, D. M. Jacob
Section 6	Spacecraft Subsystem Design Tradeoffs	A. F. Caprioglio, C. W. Renn,
Appendix A	Single Channel FM Voice Phase-Lock Loop Demodulator	R. M. Jaffe
Appendix B	The Role of Correlations in Navigation Satellite Error Analysis	D. A. Conrad, S. Y. Itoga
Appendix C	Range-Range Difference Comparison	A. J. Mallinckrodt
Appendix D	Reliability Analysis	E. H. Barnett

In addition, valuable technical information was obtained during the study through discussions with National Aeronautics and Space Administration, Federal Aviation Administration, Air Transport Association, Aeronautical Radio, Inc., Communications Satellite Corporation, the Boeing Company, and the Flying Tiger Lines, as well as international organizations such as the International Civil Aviation Organization, and the International Air Transport Association.

CONTENTS

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

TABLES (Continued)

1. INTRODUCTION

1.1 GENERAL

The purpose of this System Analyses volume is to present the nature supporting analyses that explain the selection and design of the Navigation/Traffic Control Satellite System described in Volume III, Systems Concepts. Volume III describes the operational system, the Design and Development/Preoperational system, and the programs required to bring them into being, as well as a wide number of applications to which this system can be applied. In arriving at the recommended configuration, TRW developed conceptual configurations of a number of promising candidate systems. It is the intent of this volume to describe the selection process and the reasoning that was used to select the most promising candidate configurations. This includes the development of requirements and criteria, the communications load analysis, the communications subsystem analysis, a position determination subsystems analysis, and a spacecraft design analysis.

TRW initially developed a set of functional and performance requirements using the final report of the Ad Hoc Joint Navigation Satellite Committee; the RFP study guidelines; the results of other TRW studies, as well as certain Comsat Corporation, FAA, and Radio Technical Commission for Aeronautics investigations. This preliminary requirements and criteria analysis structured the synthesis and selection process for both the position determination and communications subsystems, bounded the problem, and made certain that any selected candidate system would be capable of performing the ultimate mission. Following discussions with NASA, FAA, and other interested agencies, the final requirements and criteria were synthesized. Where appropriate, a reevaluation of candidate techniques was made. For example, the early bounding requirement of surveillance fix rate for aircraft in the North Atlantic was higher than that finally chosen by a factor of about four. The power requirement for the passive and active ranging techniques, which had been a significant comparison item, was then reevaluated to determine the suitability of the original choice. Also, in the synthesis and selection process, it became apparent early in the study that it would be possible to reject some candidate system prior to detailed analysis and comparison with all criteria.

In the communications load analysis TRW examined the impact of expected aircraft and marine communications on the design requirements and subsequent performance of the navigation/traffic control satellite. Included was a development of a queuing model, and aircraft and marine message analyses consisting of message classification, length, and frequency of occurrence. Those messages which were readily adaptable to conversion to digital format were so converted and the communications channels synthesized accordingly. This analysis was, for the most part, a requirements study, but it contained in substantial measure thought processes that were used to structure the communications subsystem in an iterative way. Because of the importance, magnitude, and nature of the communications load analysis, it was separated from the rest of the requirements and criteria analysis in this report.

The spacecraft design analysis in Section 6 is not a detailed description of the entire spacecraft design thought process, but rather presents three major tradeoffs that greatly affected spacecraft configuration, i.e., attitude control, antenna configuration, and solar array configuration. As such, Section 6 is relatively independent of the rest of the sections in this volume.

1.2 CARRIER FREQUENCY CONSIDERATIONS

Since the selection of carrier frequency spans both the position determination and the communications subsystem analyses and was a significant factor in both, and because of its very major importance in this study, the major factors influencing selection are summarized here. Discussions will be oriented towards the use of VHF, L-, C-, X-, and above X-band.

VHF (118-136 MHz) is currently a prime contender for satcom to low performance terminals such as aircraft, but is subject to major limitations of spectrum and, if initially used, would probably tend to eventually become obsolete for this service. The adaptation of this frequency band for aeronautical satcom is currently motivated by the following factors:

- Several years of pioneering effort on the part of organizations such as Pan American, ARINC, ComSat Corporation, Bendix, and Dorne and Margolin have laid groundwork for aeronautical communications in this band. Thus, the Boeing 747's which have been ordered by TWA and Pan American currently have provisions for a satcom system.

- Although none of the current aircraft VHF communications gear is suitable for satcom, if all new gear is added to an aircraft for this purpose, certain elements of this gear could be shared for ordinary VHF communications, (e.g., the preamp and possibly the output amplifier). The elements which could not be shared include the antenna and the modulation and demodulation equipment.

- The feasibility of VHF communications from aircraft through satellites has been demonstrated through existing Applications Technology Satellites.

The disadvantages of VHF are:

- Severe ionospheric refraction errors which drastically and unnecessarily limit the accuracy available for position determination.

- Limitations of spectrum

- Preference for L-band by the French, English, and Canadians (Reference 1) in a program which obviously requires their eventual acceptance. In fact, there is no significant support from any foreign nation for the VHF satcom program.

Although a band from 136 MHz to 138 MHz exists in the upper end of the aeronautical band, this is committed to space research, telemetering, and tracking. Several manned space flights have used this band as speech channels. Additionally, in Regions 1 and 3, it is shared with fixed and mobile services. While this band may be useful for the proposed service, the likelihood of approval of even a 1-MHz section is remote.

The next higher bands for radio navigation are 149.9 to 150.05 MHz and 399.9 to 400.05 MHz, neither of which holds promise of possible large bandwidths in addition to being shared with other services.

Two remaining bands are from 960 to 1215 MHz and 1300 to 1350 MHz. These bands are reserved worldwide for aeronautical radio-navigation, the former for TACAN and the latter for ground-based radars and future airborne transponders. Their reallocation within the near future is unlikely.

The L-band region from 1540 to 1660 MHz is presently allocated for aeronautical navigation services. This region is an optimum one for satellite-based navigation, traffic control, collision avoidance, and communication between low performance terminals such as aircraft and ships. The studies performed by TRW indicate that operation in this band permits very simple, single element, lightweight user antennas for navigation and relatively low bit rate data relay. For voice relay, the antenna required is still small and light but somewhat more complex in that it appears desirable to switch between three antennas.* Spectrum is available in this region and excellent navigation accuracy can be obtained as has been indicated by analytical studies, as well as military and NASA tracking systems in the nearby S-band region. The use of this region permits common communication and navigation antennas and preamplifiers for the first time. All technology necessary is currently available. Demonstration via synchronous satellite will take place in approximately one year using the ATS-E.

The proponents of VHF often claim that a serious time delay will be associated with the use of L-band as opposed to VHF. Such a time delay, however, cannot be attributed to the satellite and supporting technology as it has essentially the same status as that of VHF. If any does exist, it must, instead, be attributed to time delays associated with the acceptance by the user and the operational implementation of the use of this

*VHF satcom antennas require switching between two modes and are significantly heavier than the L-band antennas.

frequency band. Such delays can often be significantly reduced provided sufficient advantage is offered.

The C- and X-band regions are currently in use for communication satellite services. The utility of the higher frequencies such as C-, X-band, and above, at least in the foreseeable future, will be limited to large terminal fixed (as opposed to mobile) services capable of supporting and operating a highly directive antenna. As a corollary, there will be increasing pressure for the use of the lower bands (L- and S-) for satellite-mobile services, displacing the fixed services upward.

As a result of the above considerations, TRW has chosen L-band as the operating frequency for this study despite the real possibility of the development of a VHF Aerocomsat in the near future. The technology lead enjoyed by VHF: 1) is smaller than is generally appreciated; 2) is relatively insignificant when the long lead times associated with international agreements and retrofits of literally thousands of aircraft are considered; 3) and is even more insignificant when it is considered that the approach will lead to a system which would soon become saturated and outmoded, most certainly requiring an eventual changeover to L-band equipment.

The above frequency considerations are summed up in Table 1.

Table 1. Carrier Frequency Considerations

VHF (118-136 MHz)

- Technology demonstrated
- Low user antenna gain, but antenna is heavy
- Dead end approach
  - Limited spectrum
  - Poor navigation accuracy

L-Band (1540-1660 MHz)

- Small, light, simple user antenna
- Spectrum available
- Excellent navigation accuracy
- Technology exists
- Permits common communications and navigation antenna and preamp

C-Band (5000-5250 MHz) and above

- Spectrum available
- Heavy, complex, costly user antenna needed
- Technology exists

1.3 SELECTION OF NAVIGATION/TRAFFIC CONTROL SATELLITE DESIGN APPROACH

The purpose of this section is to describe and develop the selection process used in determining the preferred conceptual design of the Navigation/Traffic Control Satellite System. This section will discuss the application of the various quantitative and qualitative system requirements developed in Sections 2 and 3 of this volume; outline the reasoning used in the selection of the preferred position determination technique; discuss the allocation of voice and data channels for aviation, marine, and search and rescue operations; and finally, discuss some significant factors involved in choosing between a number of attractive satellite design approaches. The reasoning process was an iterative one, involving a great deal of interplay between steps which must be described sequentially. As such, this section will tie together a number of thought processes which are described in greater detail in later portions of the study.

The result is a system of synchronous, multipurpose satellites and supporting ground stations which provide:

- Passive navigation
- Automatic data reporting (Autorep) for surveillance
- Voice and data communications
- Potential growth to collision avoidance system.

for appropriately equipped users in most of the major global travel routes. Several major spacecraft subsystem design tradeoffs will then be treated in Section 6 of this volume; and the description of the total system concept comprises Volume III.

1.3.1 Application of Requirements

Sections 2 and 3 of this volume treat in detail the quantitative and qualitative attributes or characteristics desired for the Navigation/Traffic Control Satellite System. The most significant design requirements and a brief indication of how they affected system design are discussed in the following paragraphs.

User Base

It was clear that by appealing to a broad customer base, the Navigation/Traffic Control Satellite System would be assured of being economically beneficial at a much earlier date. This factor was rated quite heavily. The impact of this factor on system design is to indicate a need for higher performance, primarily in terms of capacity, both for position determination and communications.

Accuracy

The air traffic control surveillance analysis of Paragraph 2.4 indicated that a position determination uncertainty of 1 nmi (1σ) was an excellent design point and that greater than 3 nmi (1σ) was probably unacceptable. The collision avoidance and stationkeeping discussion of Paragraph 2.5.4 indicates that a position determination accuracy of 0.05 nmi would be useful. To be useful for aircraft low approaches at an airport, the system would have to be accurate to about 100 feet.

Capacity

As indicated in Paragraph 6.2.2.1, the desire for appeal to a broad user base made infinite capacity a desirable characteristic. Thus, since passive navigation techniques are in fact unsaturable, this played a very significant role in the selection process. In terms of communications capacity, the design approach was to avoid a gross overdesign but also to design enough capacity into the system to clearly avoid saturation problems.

Coverage

Full worldwide coverage between 70° N. latitude and 70° S. latitude was originally a design goal and is accepted for navigation coverage. It became apparent early in the analysis that to provide such communication coverage would be unnecessarily expensive. The coverage of most major trade routes and populated areas of the Western World represented a design compromise.

Reliability

One of the most significant reliability criteria postulated in Section 2 is that a total system breakdown must be an extremely rare event (e.g. once a decade). This requirement resulted in long satellite design life and design mean-time-to-failure, and indicated multiple satellite rather than single satellite designs.

1.3.2 Position Determination Technique Selection

Angle Measurement Position Determination

Concepts considered were active and passive interferometers, a spinning interferometer, and a spinning fanbeam technique. Angle measurement techniques are attractive since theoretically a single satellite will provide full North Atlantic coverage. In practice, however, the operational reliability requirement would make it almost imperative that a second satellite be on station since the entire North Atlantic air traffic control system would hinge on a single spacecraft. The accuracy of all of the high attitude angle measurement schemes considered was limited and would, at best, approach the marginal 3 nmi (1σ) figure. To obtain even adequate accuracy would require going to C-band or higher carrier frequencies, in turn requiring either high aircraft antenna gain or high satellite power. The analyses of these systems also showed that, without exception, implementation of these techniques required a development program involving higher risk, longer lead time, and despite the reduction in number of satellites, higher overall D and D costs than for range measurement concepts. Technical problems associated with attitude determination, control and/or compensation comprise the main source of risk. Even if it were possible to develop an angle measurement technique in a development program of the same scope as for a ranging scheme (and it is not), the result would be a system which is non-competitive with active or passive ranging in terms of overall system performance (in fact, hardly competitive with the Omega system). Horizontal position information would be less accurate. No altitude data would be available; nor would velocity information. Growth potential for items such as collision avoidance would be extremely doubtful. In summary, angle measurement position determination techniques were all rejected because they represented a high development risk leading to a non-competitive system approach.

Range Measurement Position Determination

A range measurement position determination scheme is considered passive if the user's position can be determined without requiring him to radiate a signal. If this determination requires such a transmission on his part, the technique is considered to be active. It should be noted that passive position determination schemes are inherently navigation devices since the user obtains the data from which his position can be determined. Most active schemes, on the other hand, involve the attaining of these data by a ground station, and can therefore be considered inherently to be surveillance systems. Clearly, a passive navigation scheme can be made into a surveillance system by use of a communications link, and an active position determination scheme can be made into a navigation system likewise by use of a communications link.

The major elements needed to compare active and passive techniques for the Navigation/Traffic Control Satellite application are given in Table 2. In terms of accuracy, the active technique is clearly better when only two satellites are in operation, and is somewhat better when three or more satellites are used, although the difference is no longer operationally significant. Satellite peak power, on the other hand, is much lower for the passive technique. The satellite average power can be lower for the passive or lower for the active, depending on the surveillance fix rate required. When the communications satellite RF power requirements are considered, however, none of these differences appear significant. Passive ranging involves much lower aircraft peak power. Finally, the aircraft user hardware costs can be made somewhat lower for the active technique.

It is clear that active ranging is a very attractive position determination technique. In fact, if one looks no further than the North Atlantic air traffic control problem in 1975, it is on a par with passive ranging. However, due to the saturability of an active ranging system, its attractiveness in supporting a broad customer base, and its growth potential for the air traffic control mission, are both limited. When these two techniques are evaluated in light of the total problem, passive navigation with the data link for surveillance is the more attractive design approach.

Table 2. Comparison of Ranging Techniques

	Passive	Active*
Air Traffic Control Surveillance		
Accuracy with:		
2 satellites	1.0 nmi/hr	0.1 nmi
3 satellites	0.1 nmi/hr	<0.1 nmi
Satellite RF Power (L-Band)		
Peak	70 w	3100 w
Average		
11,000 fixes/hr	25 w	40 w
5500	17.5 w	20 w
2200	13 w	8 w
1100	11.5 w	4 w
Aircraft Power, Peak	0.5 kw	42 kw
User Hardware Costs	≈ $13K	≈ $10K
Other Uses	Broad	Limited

*As mentioned in Paragraph 5.4.3.

1.3.3 Communications Subsystem

The communications requirement for the Navigation/Traffic Control Satellite System in the North Atlantic has been discussed in a number of areas in this report. The aviation requirements are summarized in Paragraph 3.7. From a purely communications load point of view, twelve normal voice channels and one or two 1200 bit/sec data channels were selected. In the design tradeoffs that followed these figures were modified slightly. The voice channel allocation was reduced to eleven voice (yielding similar and satisfactory performance) so that a system of three identical satellites, each providing four voice channels, could provide eleven voice and one emergency voice channels. Primarily for reasons of mechanization, which are described in Volume III, the data messages were mechanized using two data channels for Autorep and a third data channel for company communications and weather messages.

The treatment of marine and specialized missions such as search and rescue (SAR) are discussed in Paragraphs 3.8 and 2.7.3, respectively. Establishing the relative importance of these various uses was beyond the scope of the study. Fortunately, in the allocation of channels such a determination was not necessary. Examination of the nature of marine transportation, and SAR operations made it clear that both marine and search and rescue requirements thus far identified could be met using three full-time data channels for marine use, plus the excess aviation channels available during off-peak seasons and hours for marine and SAR operations. The rationale behind this is described for marine communications in Paragraph 2.6.3.1 and for SAR in Paragraph 2.7.3. Some of the mechanization aspects of providing communications to users other than commercial carrier are discussed in Volume III, Paragraph 2.3.6.

Two major questions clearly merit study which was beyond the scope of this contract. First, the worldwide communications requirement, especially in the continental United States, could differ greatly from that over the North Atlantic. Specifically, the communication via satellite requirement over the continental U.S. could conceivably be reduced to virtually zero since line-of-sight communication between aircraft and ground must of necessity already exist. On the other hand, it may be shown that the continental United States air traffic control system itself could be operated much more efficiently through more centralization and the use of a significant amount of satellite communications. Thus the communications load for satellites serving the continental U.S. could be substantially greater or substantially less than for those supporting North Atlantic Ocean Area operation. A second question is brought to mind by the Applications section of Volume III. If detailed marketing analyses show that there is substantial economic benefit to, say, commercial fishing fleets, solar flare warning nets, or spacecraft recovery operations, then the communications capability presently designed in the system would be clearly inadequate.

1.3.4 Satellite Design Approach

The study thus far has established a need for some 18 communications channels plus a position determination capability in the North Atlantic Ocean Area. The satellite portion of the system could be implemented with a number of alternate approaches:

(1) A single communications, plus single navigation satellite

(2) Multiple communications satellites, each carrying part of a load, plus a single navigation satellite

(3) A single communication satellite plus multiple navigation satellites

(4) Multiple communication satellites (again each carrying a share of the load) plus separate multiple navigation satellites

(5) A single multipurpose communications/navigation satellite

(6) A number of smaller multipurpose communications/navigation satellites.

Approaches (1), (2), and (5) require an angle measurement position determination technique, whereas the other three are compatible with ranging techniques. The primary purpose of this paragraph will be to discuss the various factors involved in choosing between a dedicated single-purpose (communications <u>or</u> navigation) satellite approach such as Approaches (1) through (4), and a multipurpose satellite approach, e.g., Approaches 5 and 6. The choice of dedicated versus multipurpose satellite will be discussed in the light of a number of considerations — communications load, position determination techniques, coverage, reliability requirements, system designs and operational strategies required to achieve those requirements, and finally, the relative cost for implementation.

<u>Communications Load</u>

The 12-voice plus 6 data channel North Atlantic Ocean Area requirement when reflected to navigation/traffic control satellite design would require approximately 3 kilowatts of in-orbit power generation capability in the case of a single synchronous satellite. Even if the communications load were to be divided into three or four satellites, the satellites themselves would be quite large — on the order of Intelsat IV or larger.

<u>Position Determination Technique</u>

As indicated before, angle measurement position determination techniques offer one attraction in that they are designed to provide user position determination with a single satellite. For the reasons described in Paragraph 1.3.2, however, these techniques, and therefore, Approaches (1), (2), and (5) can be discarded. Approach (4) can be discarded since the power required for active or passive ranging channels is quite small.

Thus the size and cost of the communications satellites would increase only slightly with the addition of the ranging channels. As a result, it would be extremely inefficient to launch multiple communications and multiple navigation satellites.

Approaches (3) and (6) then are the final contenders.

Coverage

Both approaches show advantages and disadvantages with respect to coverage. Clearly, in terms of the total area that can be covered, a multiple satellite approach has the advantage. In the case of a failure of a given satellite, either total or partial, this advantage turns into a disadvantage in that another satellite located, say, 60 degrees away in longitude, cannot fill in with the same coverage.

Reliability Requirements

Preliminary calculations show that one large communication satellite could provide something on the order of 96 percent availability service for substantially less cost (perhaps as low as one-half the cost) of using three smaller satellites which share the communications load and which provide a 99 percent availability. The results obtained are extremely sensitive to satellite configurations, launch strategies, pad availabilities, and the like. As indicated in the requirements analysis, a total system failure should be an extremely rare event. A failure of a single satellite on which the whole air traffic control system over the entire North Atlantic is depending could jeopardize the lives of some of the 10,000 people during peak travel periods. This factor makes a very strong case for a fail-soft or fail-operational capability. To obtain this capability with a so-called single satellite approach would almost definitely require a spare satellite in orbit, which would more than wipe out the cost advantage accrued to the single satellite approach. Multiple satellites, which share the load, are very unlikely to fail simultaneously, and a single satellite failure will still leave the system operational.

Launch and Spares Strategies

There are a number of launch and spares strategies which affect the reliability and cost picture and therefore a choice between the two approaches. In the event of a failure which takes the performance below an acceptable level, a number of replacement strategies could be used:

- Wait for a failure and then initiate contractual and program action to provide a replacement. Clearly this would be unacceptable in terms of down times and overall system availability. A streamlined modification of the above approach could be used wherein every attempt would be made to predict failures and to have most of the long lead time steps performed in advance. Experience on previous satellite programs indicates that down times of several months are very likely with this approach.

- Dedicated satellite launch vehicles and pads could be maintained and used in either of two ways: replacement launches could be scheduled consistent with the expected failure rate or replacement launches could be made only in the event of failures. For the single satellite approach (No. 3 above) maintaining a spacecraft, launch vehicle, and pad in readiness for the failure of a satellite which might not occur for say five to seven years, would be a prohibitively expensive approach. For the multiple satellite approach wherein failures and a total worldwide system might be expected on a quarterly basis, either of these techniques or perhaps a combination of the two appears to be worthy of consideration.

- The launching and maintenance of spares in orbit has also been investigated by TRW on another program and was shown, for that program at least, to be superior to the maintenance of a dedicated launch pad. These spares in orbit could either be redundant, i.e., located in very nearly the same location as the satellite which they are to replace, or they could be made to be movable. The preliminary design phase of the Navigation/Traffic Control Satellite program should investigate this approach carefully. The present NTCS design does not provide for rapid (one or two day) movement of synchronous equatorial satellites from one longitude to another.

It has become apparent during this study that the preliminary design phase of the Navigation/Traffic Control Satellite Study should quantify the voice, data, and ranging channel availability/reliability requirements since they have a very significant impact on the satellite design, launch and spares strategies, and operational procedures.

Cost

A factor relating to cost is the design, development, and production of different configurations of satellites. The dedicated communications, dedicated navigation satellite approach obviously requires two completely distinct satellite designs. The multipurpose satellite approach, however, offers the promise of a single satellite design. In actual practice, as will be pointed out in Volume III, the multipurpose satellite approach taken herein involves something in between, i.e., minor modifications on a single satellite design resulting in three versions which, although completely identical externally, do have internal configuration differences.

In conclusion, although the scope of this study did not allow detailed quantitative trades in the above areas, substantial experience in the analysis, synthesis, design, development, and launching of satellite systems by TRW provided a sound basis for engineering judgment. It does appear probable that the multiple, multipurpose communications/ navigation satellite design approach is the more attractive alternative.

1.4 REFERENCES

1. Interagency Group on International Aviation 77/1.30D, Final Action, "Aeronautical Telecommunications Services via Satellite -- Guidance Material on Radio Frequency Management Aspects of Aeronautical Telecommunication Satellites for Use by U.S. Spokesmen at International Meetings, dated Oct 30, 1968."

PRECEDING PAGE BLANK NOT FILMED.

2. REQUIREMENTS AND CRITERIA ANALYSIS

2.1 INTRODUCTION

2.1.1 Approach

In the development of the Navigation/Traffic Control Satellite System requirements TRW started with the concepts and guidelines outlined in the statement of work and the guidelines of the contract, and the final report of the Ad Hoc Joint Navigation Satellite Committee. In addition, TRW used inputs from the Federal Aviation Administration (FAA), the Radio Technical Commission for Aeronautics (RTCA), the Air Transport Association (ATA), as well as international and foreign organizations such as the International Civil Aviation Organization (ICAO), the International Air Transport Association (IATA), and the Centre National D'Etudes Spatiales (CNES).

The requirements study itself was conducted in three phases. The first phase, based on the foregoing inputs, was an examination of the requirements picture in enough detail to allow the synthesis and comparison of the various position determination techniques. Neither time nor resources permitted complete and quantitative cost and performance tradeoffs of each technique, but the requirements analysis at least bounded the problem and made certain that any technique chosen would be capable of performing the ultimate mission. The requirements were not made so rigid nor were they so rigidly applied that logical candidate systems were rejected because they failed to pass some arbitrary criterion. The second phase of the requirements analysis consisted of discussions with NASA, FAA, Aeronautical Radio, Inc. (ARINC), ATA, and other interested organizations wherein TRW outlined its preliminary findings and obtained feedback from various interested parties. As a result of these discussions, some requirements were modified immediately and further analyses were made that resulted in further refinements of the overall requirements picture. These final analyses and modifications comprised the third phase of the requirements analysis.

In evaluating the requirements picture TRW concentrated on the major problems associated with air traffic contron in the North Atlantic

Ocean Area. Special applications such as oceanography did not weigh heavily in the requirements, criteria, or design of the system.

2.1.2 System Concept

An outline of the Navigation/Traffic Control Satellite System concept is given in Table 3. This Navigation/Traffic Control Satellite System concept has been an outgrowth of the Ad Hoc Joint Navigation Satellite Committee and a continuing National Aeronautical and Space Administration program, both at the Office of Space Science and Applications, and at the Electronics Research Center; and was the framework on which the more detailed requirements and criteria were developed.

2.1.2.1 Basic Elements of the System

In addition to people, procedures, and the natural environment of the earth itself, there are three basic elements of the Navigation/Traffic Control Satellite System which need to be considered in its conceptual design. The first element is made up of the satellites themselves, which provide basic navigation data and high quality, highly reliable communications relay services. The second basic element of the system – called user equipment or user hardware, is made up of the electronics equipment used by the various system customers. It consists of antennas, receivers, data processors, displays, and the like. The third major element of the system is made up of the various ground stations which provide satellite system support such as satellite tracking and station-keeping, and user mission support such as air traffic control, meteorological advisory services, and relay of company communications.

2.1.2.2 Functions

The Navigation/Traffic Control Satellite System must be configured so that the following functional services can be provided:

- Communications
- Surveillance
- Navigation
- Collision Avoidance.

Table 3. Navigation/Traffic Control Satellite System Concept

ELEMENTS

- Satellites
- User Equipment
- Ground Stations

FUNCTIONS

- Communications
- Surveillance
- Navigation
- Collision Avoidance

USERS (BY 1975)

- Large Aircraft
- Large Ships
- General Aviation, Small Marine

COVERAGE

- North Atlantic Ocean Area (Primary)
- Worldwide

The communications, surveillance, and navigation functions make up the basic elements of a number of missions, such as air traffic control, search and rescue operations, and recovery of manned and unmanned spacecraft. Other missions, such as scientific or commercial exploration, usually involve two or more of these functions. In the air traffic control mission, which is the one considered in greatest detail in the Mission Study, the relative emphasis and importance of all four basic functions will vary between the North Atlantic case and the Continental United States case, and will in all likelihood vary significantly. The very nature of the aircraft and the air traffic control system changes. For this reason it is important to examine in the early conceptual phase the potential roles and the suitability of this system in playing those roles, and to configure the system so it is capable of performing any or all suitable roles.

2.1.2.3 Users

The Ad Hoc Joint Navigation Satellite Committee made it clear that there was a wide range of potential customers for such a system. NASA has, from the outset, intended that the operational system be available and economically beneficial to a broad spectrum of users including:

- Large aircraft
- Large ships
- General aviation
- Small marine craft
- Specialized users such as scientific projects or expeditions.

The reason that the Navigation/Traffic Control Satellite System should cater to a broad spectrum of users is simply one of economics. There is general agreement that the reduction in separation standards of aircraft over the North Atlantic would, in itself, provide economic benefits and increased safety that would justify the existence of the Navigation/Traffic Control System. General agreement does not exist, however, as to the degree of benefit provided or the year in which the break-even point would occur. It is obvious, however, that the Navigation/Traffic Control Satellite System will be more useful and of greater economic benefit if it can be applied to a wide variety of uses by many different subscribers.

2.1.2.4 Coverage

The Ad Hoc Joint Navigation Satellite Committee recognized that an immediate need exists for a more efficient air traffic control system over the North Atlantic Ocean. For this reason the North Atlantic Ocean area has received primary emphasis in the study; but, recognizing the obvious benefits of a worldwide system of this type, NASA incorporated into the study requirements the ability of the system to function on a worldwide basis, and called for an examination of the impact on the system design caused by expansion to worldwide coverage.

2.1.3 General System Characteristics

The following guidelines were used throughout the study in the synthesis and evaluation of candidate systems. They are qualitative, rather than quantitative in nature, but they are nonetheless real, and they have contributed significantly to the shaping of the system. In some cases, specific quantitative criteria were developed that go beyond these qualitative general requirements and criteria.

2.1.3.1 Functions

Obviously, to fit the basic concept the recommended system must be capable of performing or contributing to the performance of the four basic functions of communications, surveillance, navigation, and collision avoidance.

2.1.3.2 Initial Operational Capability

The system must be developed and demonstrated by 1975.

2.1.3.3 User Base

The system should be operationally beneficial and economically within the reach of a broad base of users or operators.

2.1.3.4 Operational Flexibility/Adaptability

One of the most important characteristics which can be designed or built into a system such as this one is the ability on the part of the ultimate operator or consumer to use the system in a number of ways, not all of which need be designed into the system at the outset. If there is one certainty in the field of transportation during the remainder of this century, it is the certainty of change. As the needs of the traveler and the mode of travel change, the requirement for the ability of such a system as this to adapt to those changes becomes extremely important. Even in the absence of changes in, say, the types of aircraft served by this system, if the system has what is commonly called operational flexibility, the ingenuity of the air traffic controllers and pilots will find ways to adapt the system to its environment, thereby enhancing its overall usefulness and prolonging its life. An example of this type of ingenuity is discussed in Reference 1.

2.1.3.5 Evolutionary Growth Potential

The system must be capable of being phased into the aviation and marine environments such that it will not displace present systems overnight. Furthermore, the system must be capable of providing growth in the services provided just as the customer base itself will certainly grow. The reasons for evolutionary rather than revolutionary change in hardware or procedures are primarily twofold. First, it is simply not economical nor feasible for commercial carriers to replace equipment which is operating even adequately before they have recovered their investment of that equipment. Second, they will not make such a change until it is clearly demonstrated that it is both beneficial to them and safe for them to make such a change. But all these changes do take place, and a system which demonstrates evolutionary growth potential serves its community better and longer than one flashy innovation which is soon replaced by another. The old low-frequency radio ranges served the aviation community in the United States for a long time. The present VHF omni ranges are expected to do the same, and it seems relatively certain that, if it is correctly designed, the Navigation/Traffic Control Satellite System can do the same.

2.1.3.6 System Performance

The performance of this system should, for any particular user, be adequate to allow him to perform his mission but any particular user should not have to pay for performance which he cannot use. The system as a whole, then, must clearly meet the needs of its broad customer base but should not be grossly overdesigned. For example, at the very outset of Navigation/Traffic Control Satellite System service, the full number of voice channels required by a peak population of aircraft in the North Atlantic, need not be provided since they will not have all been retrofitted to use this equipment at that time.

2.1.3.7 Accuracy

The system should have the capability of providing very high accuracy position determination for those users who are able to pay for it. Operational flexibility and adaptability will be enhanced if good accuracy data is or can readily be made available.

2.1.3.8 Capacity

Although, as just previously mentioned, it is not desirable to have capabilities that are grossly in excess of system needs, the system capacity in terms of voice and data communications channels, and position determination fix rates must be adequate to handle peak loadings such that system breakdowns and the resulting loss of confidence in the system do not occur. Furthermore, since in the field of transportation we continually and consistently tend to underestimate the needs of the traveling public, a certain capacity margin is indicated.

2.1.3.9 Availability

Full-time coverage over all major oceanic air and marine transportation routes must be available.

2.1.3.10 Reliability

Although the economics of any satellite system dictate that the reliability of the system be very high, the reliability aspects of the Navigation/Traffic Control Satellite System differ greatly from a scientific observation or commercial communication satellite. When applied operationally, this satellite system will affect the safety of literally thousands of airline travelers, and will be affected very significantly by the characteristics of the user's own equipment. The safety aspect requires that the system be "fail/operational" or "fail/safe." A total system breakdown must be an extremely rare event (e.g., once a decade) and single failures must not produce catastrophic results. That is, if a single satellite were to be lost in the operational system, the remaining satellites should be capable of carrying an operationally acceptable percentage of the load. Further, the ground system should be made with enough redundancy and ease of maintainability that ground station reliability should have an insignificant effect on overall system reliability. Finally, since the majority of the users of the system will be in a competitive commercial situation, high reliability and maintainability must be balanced against initial and operating costs, and the traffic control system must be able to tolerate a few aircraft with inflight NTCS equipment failures.

2.1.3.11 Cost

In order to be economically feasible as well as beneficial to a broad user base, costs must obviously be as low as possible. In the operational case this means that costs must be commensurate with the performance (say, accuracy) requirements of the user. For example, in addition to a relatively expensive, high accuracy, automatic navigation system for a jet aircraft, low cost sets should be available to, say, small marine craft whose fix accuracy and frequency requirements, and vehicle speeds are all low. In a design and development sense this means that system performance characteristics such as reliability and maintainability and design must be weighed against development risk.

2.1.3.12 Compatibility

The system must be capable of providing a full service to the user, i.e., an aircraft or ship must have the capability of using a self-contained satellite navigation system requiring no other input such as inertial LORAN or other navigation aids. The one exception to this is that aircraft may provide their altitude as input data. On the other hand, this satellite navigation system must be compatible with use in combination with these other navigation aids, although not dependent upon them.

2.2 COMMUNICATIONS

A significant portion of the Navigation/Traffic Control Satellite Mission Study was spent in examining the major elements of requirements for reliable, full-time air/ground communications in transoceanic flight. A communications load analysis was performed which examined the nature and scope of aircraft and marine communications anticipated in the North Atlantic region in 1975 in order to determine the number of communication channels required for a Navigation/Traffic Control Satellite System. This portion of the requirements analysis is discussed in detail in Section 3.

The recommended North Atlantic Ocean Area communications capacity for the Navigation/Traffic Control Satellite System which came from the analyses of Sections 3 and 4 is shown in Table 4.

Table 4. North Atlantic Communications Requirements

AIRCRAFT

- 11 voice (peak load)
- 1 emergency voice
- 3 data

MARINE

- 2 data
- 1 emergency data
- Off-peak aircraft voice

SEARCH AND RESCUE

- Preempt 1 or 2 aircraft voice

The second communications guideline from Reference 2 states that "communications should be for air traffic control purposes; transfer of weather, oceanographic and emergency data; and information of the status of the craft." The first two categories of information clearly pertain to information exchange between air and marine craft and those governmental agencies responsible for traffic control, meteorological, and advisory services. The last item relates to relay of information between commercial aircraft and their own company flight operations. Thus TRW interprets this last item to mean relay of all company information, e.g., information on passengers, cargo, and the like, as well as status of the craft itself. It does not matter whether the company communications are handled on the ground by a communications station such as ARINC or International Aeradio, or whether the company communication is actually processed by the governmental agencies, such as the Traffic Control Center. From a Navigation/Traffic Control Satellite System point of view the requirement exists that this information can be generated onboard the aircraft or at a ground station transmitted through the satellite and received and processed at the other end. Company communications can be a very large or very small percentage of the total communications load, depending primarily on the economics of such communication. Since general agreement has yet to be reached on this subject, from a Mission Study point of view, we will require only that the system be able to handle some reasonable amount, say, typical of that being transmitted today.

2.3 NORTH ATLANTIC AIR TRAFFIC CONTROL

2.3.1 Air Traffic Control – Purpose and Functions

The purpose of air traffic control is to provide for safe, reliable, and efficient flow of air traffic. The safety requirement is, of course, paramount and renders intolerable mid-air collisions between commercial transports or even, for that matter, near misses. For this reason, collision situations, i.e., situations wherein moving craft are in such close proximity that a collision can occur, are considered unacceptable. The air traffic control system herein will be designed such that, in the absence of multiple failures, violations of air space by controlled aircraft can be averted and the system will remain unsaturated. As pointed out by Halaby in Reference 3, travelers also want schedule reliability, i.e., they want to arrive at their destination at the time promised by the airline schedule. For this reason, systems with built-in bottlenecks and the inevitable queues that result create a negative reaction on the part of the traveling public which the aviation community is actively seeking to avoid. The air carriers themselves, of course, wish to avoid queues because of the third factor, i.e., efficiency. Nonoptimum/optimum flight plans and time spent in holding patterns prove expensive to the air carriers, not only because of the fuel expended but, more important, added logged time by the aircrews, maintenance overtime, and all the compounded problems associated with numerous delayed arrivals.

Air traffic control systems today are built around the first three required functions of the NTCS system, i.e., communications, surveillance, and navigation. Communications in this context are made up of a transfer of information between moving craft and ground stations or between various moving craft, primarily for the purposes of control, reporting, and advisories. This communication may be via voice links or digitally encoded information sent over data link, either in teletype or some other coded form. This information can be related to position determination, i.e., it could be a reporting of position or the transmittal of position data for computation on the ground. The term "data communications," as used in this report, however, will not include basic ranging signals per se. Surveillance as used herein means the knowledge and use of one or more users' position by another user. Typically, this will mean for air traffic control the obtaining of position data for various aircraft, the processing of this data, projection to future positions, and conflict search and resolution. Surveillance will not include the active command and control steps which are performed over communications links. Navigation as used herein will be considered to mean navigation in its most complete sense, i.e., determination of its own composition by a user in such a way as to perform track-keeping to an acceptable degree. Thus, the adequacy of the entire navigation, guidance, and control function is considered here.* For a fixed user, e.g., a scientific or surveying ground party, navigation would imply simply the determination of position. The satellite function in a position determination process would be to provide the basic radionavigation signals by which user position is determined. This radionavigation process could be active or passive ranging, range differencing, angle measurements, or some combination of these techniques. It is highly probable that in the future the fourth functional block will play a significant role in air traffic control. The so-called Collision Avoidance System (CAS), (or its simpler counterpart, the pilot warning instrument) will be designed to avert a mid-air collision between equipped aircraft in the event of a collision situation encountered by those aircraft; either because of a breakdown in the air traffic control system or because the aircraft are in an area not serviced by the system. Overlaid on these functions is the task of managing them properly to effect safe, orderly, expeditious flow of air traffic. It is in that context that these four basic functions will be examined in the development of the overall system requirements for the North Atlantic.

A short discussion of the differences between positive air traffic control and indirect flight following is in order. The term air traffic control as used in this report implies essentially full-time, real-time surveillance of aircraft by the traffic control agency. Real time surveillance is defined to mean examination of aircraft position data at a high enough frequency such that aircraft cannot commit airspace violations between surveillance fixes unless they make extremely gross flight path deviations. (The magnitude of the maximum allowable deviations is discussed in subsequent paragraphs.) Reference 4 refers to such control

*The reason for this seems clear. In an air traffic control sense, if an aircraft is able to determine its position only once in 15 minutes and if the determination process takes several minutes, most of the usefulness of a very high accuracy system is lost. That is, if an aircraft drifts 30 miles off course between fixes, it is of little consequence to know the magnitude of that drift to the nearest 50 feet. On the other hand, if the aircraft can close its flight control loop fairly tightly around an accurate navigation system, then its flight path will be predictably well-behaved.

as "tactical control" and requires that the knowledge of aircraft position be obtained by an "independent means under the control of the ATC Agency." Furthermore, Reference 4 stresses the importance of this surveillance data providing accurate relative positions of the various aircraft. Flight following, on the other hand, is a much looser form of control. Knowledge of aircraft position by the controlling agency is obtained indirectly and usually with very significant time lags — on the order of several minutes. This position information is obtained by each aircraft using whatever means of navigation that aircraft has available. As a result, the relative position accuracies are no better than the individual absolute position accuracies. Furthermore, there is no direct pilot-to-controller communication for either normal or emergency messages.

2.3.2 Description of Air Traffic in the North Atlantic

The majority of aircraft that fly the North Atlantic connect the eastern seaboard of the United States with European capitols such as London and Paris; although there are a number of flights across the so-called Polar routes, e.g., from Los Angeles to Scandinavia. The latter traffic, although it imposes a communications and navigation requirement on the Navigation/Traffic Control Satellite System, does not impact the major problem — which is air traffic control of a rapidly increasing number of aircraft flying the principal path between New York/Washington, and London/Paris. Also, in this principal path area there is very little crossing traffic, such as that produced by a flight from Iceland to Ascension Island. Furthermore, when the traffic is heavy going eastbound, it is light going westbound, and vice versa.

The foregoing set of traffic flow characteristics results in a pattern for air traffic in the North Atlantic Ocean area, which is fairly typical of major over-ocean air routes. Clearly, all aircraft would like to fly the optimum path between their points of departure and destination. Since the various points of departure and destination are relatively close together when compared with the long over-ocean route itself, the air traffic is placed in a number of lanes or corridors. These lanes represent controlled airspace, but they vary in geographical configuration from day to day, depending primarily on weather conditions. As in Continental U.S. traffic control, aircraft are assigned flight levels which are as close to the requested altitudes as traffic conditions and separation standards will allow. The aircraft are served on a first-come first-served basis, and an aircraft is given a lane and an altitude which is as close to optimum as possible. When traffic gets heavy, aircraft may be routed 240 nmi to the north or south of their desired course. The attempt to squeeze aircraft as close to the optimum flight path as possible is essentially the point of the Navigation/Traffic Control Satellite Mission Study.

For the period 1975 and beyond it is reasonable to expect that the nature of air traffic in the North Atlantic will be similar in most respects to the traffic situation just described. The United States supersonic transport and the British/French Concorde will, of course, fly much faster and higher. However, as indicated earlier, they are, nonetheless, turbojet aircraft and their flight characteristics exhibit the same general characteristics as the subsonic transports with regard to factors such as temperature effects on performance. Certainly differences exist; for example, the sonic boom considerations on arrival and departure. Except for the primary problem considered herein, i.e., air traffic control out over the North Atlantic, the similarities outweigh the differences. Many of the changes in air traffic control procedures then will be keyed to items such as data link communication and automated functions on the ground. With a system that provides air traffic control with high accuracy, frequent surveillance fixes, positive identification, efficient communications, and generally well-behaved aircraft, even more (not less) flexibility is possible, despite a significant increase in population and reduction in separation standards.

Typical present separation standards in the North Atlantic are as follows:

- Lateral separation — 120 nmi
- Longitudinal separation — 15 minutes
- Altitude — 2000 feet.

To date the vast majority of the efforts to reduce separation standards have been concentrated in the area of lateral separation standards, which will also be the major item treated herein. The longitudinal closure rates can be very large in the case of dissimilar aircraft flying in the same lane, e.g., if the lead aircraft were to go into a circular holding pattern (which would be legal under his clearance), very high closure rates and a collision situation could result. With real-time surveillance, however, significant longitudinal space savings can be achieved, and certainly the motivation for doing so exists. Vertical separation standards will probably remain static for some time due to limitations in the state of the art of barometric altimetry and in the absence of almost any meaningful statistical data on the ability of aircraft to hold an assigned altitude. Clearly, good altitude data for the surveillance function would be very useful here.

2.3.3 Forecast of Aircraft Population in the North Atlantic Region — 1975

Clearly, in order to quantify the system requirements associated with control of air traffic, the air traffic itself must be quantified. The purpose of this paragraph is to describe this process. The number of aircraft flying the North Atlantic Ocean area undergoes significant seasonal and diurnal variations. Our analysis, based upon peaks, will clearly yield the peak Navigation/Traffic Control System performance requirements. The area under consideration is assumed to be that North Atlantic Ocean Area normally traversed by aircraft between the United States and Canadian airfields, and European and Mediterranean airfields. To determine the maximum number of aircraft in flight simultaneously in this area, available forecasts of traffic volume were reviewed (References 2, 5-10). Most of the references cited defined the North-South boundaries of the Atlantic Ocean Area as being between 60 and 45 degrees latitude. However, for this study a larger region is considered, i.e., the Northern limit of coverage is 70 degrees North latitude. Although most of the above references were not specific about the East and West boundaries of the area of interest, it is assumed that most included that portion of the route which is not within line-of-sight communications range of land-based air traffic control ground stations. For this study, again, a somewhat larger area is considered more suitable. For this analysis the limits are made up of a Western boundary approximately 200 miles east of New York and an Eastern boundary approximately 200 miles west of London. This area will be defined as the North Atlantic Ocean Area (NAOA). A summary of the forecasts that were examined is presented in Figure 1 which shows that some observers reported on total traffic, whereas others specified both subsonic and supersonic aircraft. From Figure 1 the estimate specified by Reference 2 (Contractor Guidelines), shows that the maximum volume of traffic in the North Atlantic corridor in 1975, at any given time, will probably be approximately 170 subsonic and 20 supersonic aircraft. Hence, the Contractor Guidelines are not overly conservative but appear to represent an average estimate of traffic volume for 1975.

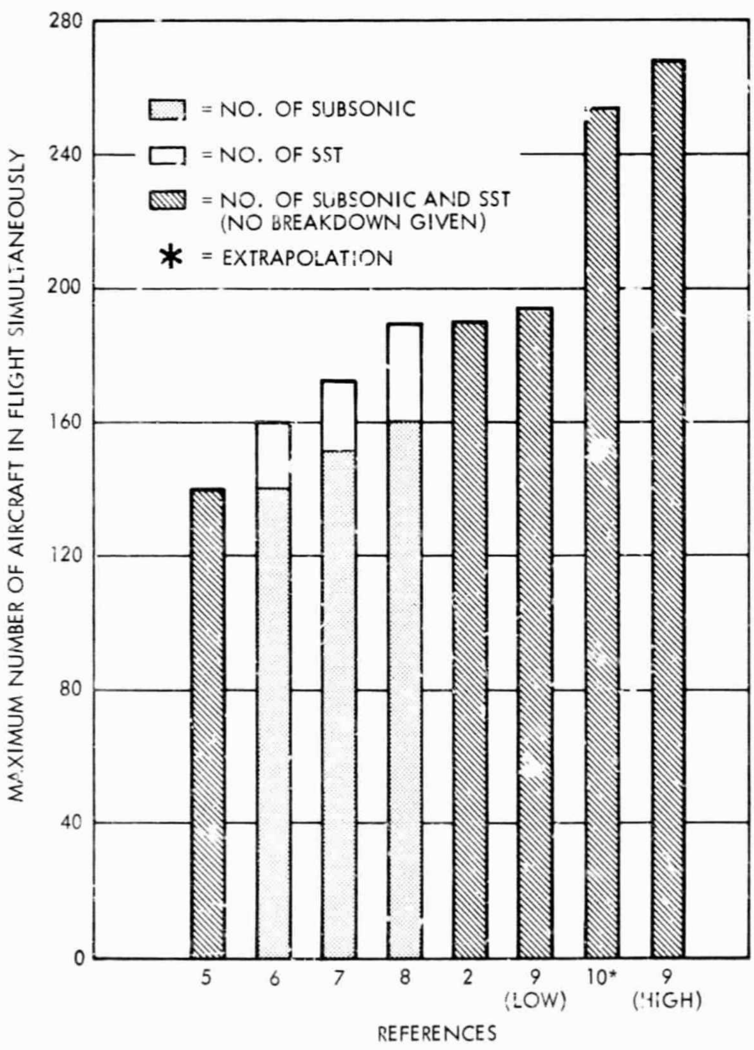


Figure 1. Summary of Peak Aircraft Traffic Forecasts for the North Atlantic Ocean Area (NAOA) - 1975.

2.4 SURVEILLANCE

2.4.1 Introduction

In this section lateral separation standards, position determination accuracy, position determination frequency, the magnitude of aircraft track errors, pilot and system reaction time, and aircraft turning performance are considered; certain quantitative relationships between those parameters are developed; and a set of requirements for en route surveillance of air traffic in the NAOA in 1975 is developed. It is the objective of the system to prevent air space violations by taking note at the air traffic control center of an impending violation far enough in advance to allow the air traffic controller to warn the pilot in time to prevent him from flying into an adjacent lane of traffic. This model assumes reliable communications and both the willingness and the ability of the aircraft to respond to the warning and/or the corrective heading instructions of the air traffic controller. Major results of this analysis are shown in Table 5.

Table 5. Recommended Air Traffic Control Surveillance Requirements

For 60 nmi Lateral Separation 1975:	
Accuracy:	1 nmi (1σ) Position Uncertainty
Fix Rate:	Subsonic - 1 fix per 80 to 100 sec
	Supersonic: 1 fix per 20 to 24 sec
	Total: 10,000 to 12,000 fixes/hr*
Provides:	≥5 observations of heading error blunders of ≥15 deg

*Requires one 1200 bit/sec data channel at ~60% duty cycle plus one 1200 bit/sec data channel at very low duty cycle.

2.4.2 Development of Surveillance Model

Figure 2 indicates the more significant parameters involved in the development of the relationship between lateral separation standards, surveillance accuracy, surveillance fix rate, and aircraft performance.

As indicated in Figure 2, each assigned lane of traffic is broken into five zones — a center zone, two surveillance zones, and two buffer zones.

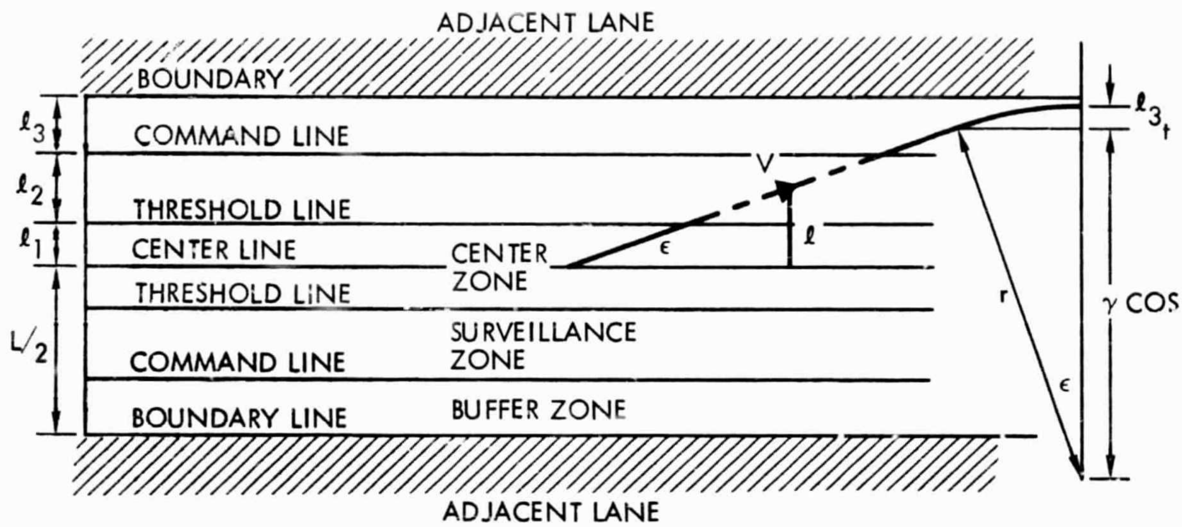


Figure 2. Surveillance Model Geometry

The center zone is bounded by two threshold lines, so named because lateral deviations from the precise center line of the lane that stay below some threshold distance will either be too small to observe or too inconsequential to trigger any significant action on the part of the system. ℓ_1, the distance from center line to the threshold line might be simply a direct function of the uncertainty in surveillance position determination. On the other hand, it might be substantially larger if historical experience of aircraft trackkeeping kinematics showed a large amount of insignificant meandering quite close to the lane center line. Finally, ℓ_1 might be zero, meaning that aircraft would continually be under observation in the conflict search sense.

The buffer zone is created to allow for two factors. First, a certain amount of reaction time is required for the air crews to receive, understand, acknowledge, and initiate compliance with the command or warning from air traffic control. Second, even after a turn toward the center line of the airway is initiated, the distance from the center line will continue to increase until the aircraft has reached a point in its turn where it is parallel to the center line. Obviously, the aircraft going off course must be given a warning or command prior to reaching the command line. It is clear then, that the surveillance task of observation, decision making, and issuance of a command on the part of a traffic controller must take place while the aircraft are in the surveillance zone.

Another very significant, and often overlooked item in this portion of the analysis is that there should be a number of observations or fixes during the period of time it would take some errant aircraft to cross the surveillance zone. This is treated as a parameter in the analysis. This analysis will assume that the aircraft in question maintains a constant speed, constant heading, flight, and is off course from a desired straight center line flight path by a constant angular error ϵ. A summary of the surveillance model nomenclature is listed in Table 6.

Table 6. Surveillance Model Nomenclature

Symbol	Definition	Units
L	Lane width	nmi
ℓ	Instantaneous distance from the lane center line	nmi
$2\ell_1$	Width of the center zone	nmi
ℓ_2	Width of each surveillance zone	nmi
ℓ_3	Width of each buffer zone	nmi
V	Aircraft speed (assumed constant)	knot
ϵ	Aircraft heading error (assumed constant)	deg
σ	Surveillance position determination uncertainty (see Para 2.4.3.4)	nmi
t	Time	hr or min.
t_i	Time to cross zone "i"	hr or min.
t_r	Reaction time	hr or min.
t_t	Time to complete a 360° level turn	hr or min.
n	Number of observations of an aircraft – during its transit of the surveillance zone	
t_{i_n}	Time between observations in zone "i"	hr or min.

From Figure 2, it can be seen that the lateral distance travel during a time t

$$\ell = Vt \text{ Sin } \epsilon \tag{1}$$

Therefore, the time to cross any zone of width

$$\therefore t = \frac{\ell}{V \text{ Sin } \epsilon} \tag{2}$$

Note at this point V is in knots and t is in hours. Now, since at the time to turn an aircraft through an angle

$$\therefore t_{\epsilon} = \frac{\epsilon}{\dot{\epsilon}} \tag{3}$$

and since the distance along an arc, s, which the aircraft travels during that time

$$s_{\epsilon} = Vt_{\epsilon} = r\epsilon \tag{4}$$

and from Figure 2 it can be seen that the lateral distance covered in the turn portion of the buffer zone

$$\ell_{3_t} = r(1-\cos \epsilon) \tag{5}$$

and since

$$\therefore r = \frac{Vt_r}{2\pi} \tag{6}$$

substituting Equations 5 into 6 yields

$$\ell_{3_t} = \frac{Vt_t}{2\pi} (1-\cos \epsilon) \tag{7}$$

Defining t_r as the reaction time; substituting in Equation 1; adding that to Equation 7; and converting time into minutes yields:

$$\therefore \ell_3 = \frac{V}{60}\left[t_r \text{ Sin } \epsilon + t_t \frac{1-\cos \epsilon}{2\pi}\right] \tag{8}$$

which is the total lateral distance travelled from the time a command is issued by the air traffic controller to the time the aircraft turns through a heading which is parallel to the center line of the assigned lane. It is this distance which must be allowed for in order to prevent airspace violations.

From Equation 2, the time in minutes to cross the surveillance zone is 15°:

$$t_2 = \frac{60\,\ell_2}{V \text{ Sin } \epsilon} \tag{9}$$

If at least "n" observations are required during this crossing, the maximum time between observations is

$$t_{2_n} = \frac{60\,\ell_2}{nV \text{ Sin } \epsilon} \tag{10}$$

Accounting for observation error complicates the picture slightly, as indicated in Figure 3. Suppose an aircraft actual track is indicated by a line AA'. Because of surveillance determination errors this aircraft could have any apparent track between BB' and CC'. In the BB' case, the observed position would not come down into the surveillance zone until the aircraft was well within that zone and the aircraft would in fact be

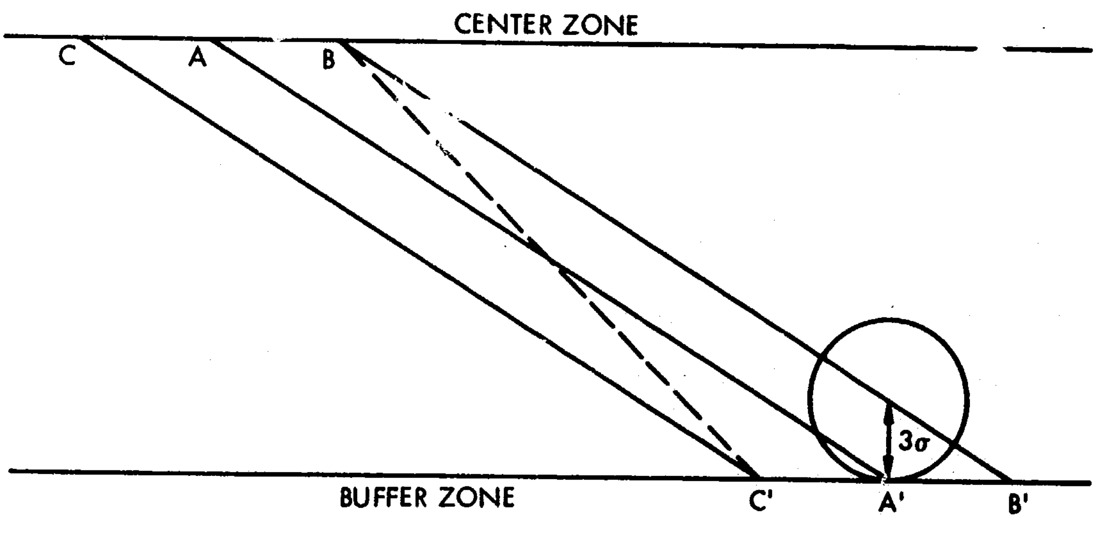


Figure 3. Apparent Versus Actual Tracks

in the buffer zone while the indicated track was still crossing the surveillance zone. Accordingly, Equation 10 is modified to account for this anomaly. Guarding against a 3σ error in the worst direction yields:

$$t_{2_n} = \frac{60 (\ell_2 - 3\sigma)}{n \text{ V Sin } \epsilon} \tag{11}$$

Although there are a number of other interesting anomalies associated with various apparent track/real track combinations, as long as the time between observations is less than t_{2n} the surveillance system will provide at least "n" observations during an accelerated crossing of the surveillance zone. Now, since the frequency is the reciprocal of the time interval between fixes for earth individual aircraft:

$$f = \frac{1}{t} \text{ in fixes/min.} \tag{12}$$

and the total number of fixes for each type of aircraft:

$$F_{sub} = n_{sub} f_{sub} \quad \text{fixes/min} \tag{13a}$$

$$F_{SST} = n_{SST} f_{SST} \quad \text{fixes/min} \tag{13b}$$

where from Paragraph 2.3.3, $n_{sub} = 170$ and $n_{SST} = 20$. The total Navigation/Traffic Control Satellite System surveillance fix rate in fixes per hour:

$$F_{NTC} = 60 (F_{sub} + F_{SST}) \quad \text{fixes/hr} \tag{14}$$

2.4.3 Discussion of Parametric Values

2.4.3.1 Lateral Separation Standards (Lane Widths)

The lane widths considered here will be 120, 90, 60, and 30 nmi as will be seen in the analysis. Sixty nmi lateral separation standards appear to be about right for the 1975 to 1980 era.

2.4.3.2 Aircraft Performance

Ground speeds of 600 knots for subsonic jets of the 707/747 category and 1800 knots for the supersonic transport category are assumed. The 1800 knot figure allows for some 250 knots over and above the projected SST true air speed to account for possible strong tail winds associated with jet stream activity, and also some aircraft performance growth. In the turning analysis, it will be assumed that subsonic aircraft are turned at 3 degrees per second while the supersonic are turned at 1.5 degrees per second.

2.4.3.3 Heading Errors

It is expected that in the 1975 era and beyond, heading errors of greater than 5 degrees will be quite rare. In fact, there are indications that heading errors of greater than 4 or 5 degrees are experienced less than 2 percent of the time today, but by the same token, lateral position errors of greater than 45 nmi were recently observed (Reference 13) on approximately 1 percent of the radar observations performed in the North Atlantic. As pointed out by Poritzky in Reference 11, it is the blunders or gross errors that the surveillance system should guard against. Thus, heading errors larger than 5 degrees must be considered. Dunmire in Reference 12 examined heading errors of 5, 10, and 20 degrees for subsonic aircraft and 1, 5, and 10 degrees for SST's. Philco in Reference 4 examined heading errors of 10 and 30 degrees. Here, heading errors of 5, 10, 15, and 30 degrees will be considered. It should be pointed out that heading errors can resolve from other than doppler radar, inertial navigation or other purely navigational errors. If for example, at a 15-degree dog leg in an airway, an aircrew became preoccupied with some onboard flight problem and did not turn to the new heading at the prescribed point, clearly a 15-degree heading error would ensue.

One very significant point to consider in evaluating the magnitude of heading errors which the system must account for is the fact that not all aircraft flying the North Atlantic will be equipped with reliable, redundant, and accurate inertial navigation systems. There will undoubtedly always be small new airline companies getting their start with older equipment;

and perhaps the air crews themselves might not be as well trained as they should be. The SST's themselves may well experience some avionics anomalies early in their service. Thus, the population of aircraft flying the North Atlantic can be expected to exhibit a fairly wide range of track-keeping abilities. Therefore, the surveillance system here will be designed to guard against errors of about 15 degrees.

2.4.3.4 Surveillance Position Determination Uncertainty

In order to establish the relative utility of various position determination accuracies, a range of σ from 0 to 10 miles is considered.

2.4.3.5 Reaction Time

Since in this analysis it is possible and therefore allowable for the last surveillance observation to take place just before the aircraft leaves the surveillance zone and enters the buffer zone the reaction time must include:

- air traffic control data processing.
- air traffic control decision making.
- the communication process (voice and/or data).
- reception and verification of the command message (verification may well include an independent aircrew evaluation of the correctness, validity, and/or advisability of the command).
- decision making process and acknowledgement.
- initiation of the commanded maneuver (this includes rolling into the bank angle required to generate the turning rates referred to above).

2.4.3.6 Minimum Number of Observations in Surveillance Zone

Multiple fixes in the surveillance zone are desirable for a number of reasons:

- Multiple fixes allow establishment of trend information.
- Trend data allows the use of better, more sophisticated criteria for warning (the computation of time to go).
- Fewer false alarms will result since aircraft whose lateral deviations stop growing need not be issued a "return to center line" command.

- Operational flexibility is enhanced (e.g., Air Traffic Controllers can vector craft around virtually on a real-time basis as do ground control approach and ground control intercept operators with present day radar equipment).

- Multiple observations are also advantageous in that in the presence of an occasional garbled fix or drop out, the system will still have ample data to work with.

A false alarm can be defined as a situation wherein an aircraft is given a "return to center line" command, when in fact such a command would be unnecessary. If the fix rate is slow enough, such that there may be only one observation of an aircraft as it passes through the surveillance zone, then clearly that observation must trigger a return to center line command. Unless the center zone is made very wide and the surveillance zones quite narrow, then the false alarm rate can be expected to be quite high. The high false alarm rate would quite possibly require a higher communications load and more bandwidth (just to broadcast the false alarms, not to mention settling the ensuing arguments!) than would the higher fix rate itself. Furthermore, high false alarm fix rates would prove annoying to air crews and controllers alike and would degrade confidence in the system. The other approach, i.e., the narrow surveillance zones would prove self-defeating in that a relatively high fix rate would be required to assure even a single observation for an aircraft transiting the zone. In short, the n = 1 case appears very impractical.

Values of "n" of 1, 5, and 10 are examined here in order to indicate the effects of variations in this requirement. Although the scope of the study has not allowed optimization of "n" in terms of bandwidth or total system cost, TRW feels that a value of 3 is probably an absolute minimum for a practical system, whereas the value of 10 is undoubtedly too high, since the added information content between n = 5 and n = 10 does not appear to be worth the added expense in terms of communications bandwidth and satellite power. Five observations appear to be a good design value at this point, and will be so "recommended."

2.4.4 Numerical Results and Discussion

Assuming a 60-second reaction time and that $\ell_1 = 3\sigma$, and solving Equation 11 for the maximum allowable observation intervals for the values of the various parameters just listed yields Tables 7 and 8.

2.4.4.1 Lateral Separation Standards

From Tables 7 and 8 it can be seen that a surveillance position determination uncertainty (σ) of 10 miles is too large for even 120 nmi lateral separation standards. This is evidenced by the fact that the maximum allowable observation intervals have gone to zero. For the larger separation standards (90 and 120 nmi) a σ of 3.3 nmi is acceptable, and for accuracies as good or better than that value the fix rate requirements are relatively low. However, if the lateral separation standards are reduced to 60 nmi the fix rate requirements for a σ of greater than about 2 nmi re prohibitive. It can also be seen that 30 nmi separation standards are not possible without a σ of 1 nmi or less.

Maximum allowable observation intervals, t_{2_n}, for subsonic and supersonic aircraft with 60 nmi separation standards are plotted versus surveillance accuracy and heading errors in Figures 4 and 5, respectively. It should be noted from these figures that t_{2_n} becomes zero at values of σ which are well under 10 miles. Since, as t_{2_n} approaches zero, the total fix rate approaches infinity, these figures must be treated as upper bounds on position determination uncertainty. Examination of Equation 11, from whence these figures come, shows that this upper bound is not a function of "n", the number of observations required during a crossing of the surveillance zone. The values of t_{2_n} at $\sigma = 0$ indicate maximum allowable intervals for high accuracy systems, and it is seen that these intervals are not unreasonable.

2.4.4.2 Accuracy Versus Fix Rate

The required number of surveillance observations per hour, i.e., the fix rate, is plotted against surveillance position determination uncertainty for various heading errors in Figure 6. When one examines this figure it becomes clear why certain organizations are claiming today that accurate position determination for surveillance purposes is not required.

Table 7. Surveillance Fix Rates, Subsonic Jets

t_{2_n}, Maximum allowable interval (in minutes) between fixes to obtain $\geq n$ observations during a crossing of the surveillance zone (subsonic aircraft, V = 600 K)

σ \ ϵ	5^o			10^o			15^o			30^o		
	n = 1	n = 5	n = 10	n = 1	n = 5	n = 10	n = 1	n = 5	n = 10	n = 1	n = 5	n = 10
L = 120 nmi												
0	67.8	13.6	6.8	33.5	6.7	3.4	22.1	4.4	2.2	10.9	2.2	1.1
1	61.0	12.2	6.1	30.1	6.0	3.0	19.8	4.0	2.0	9.7	1.9	1.0
3.3	44.9	9.0	4.5	22.0	4.4	2.2	14.4	2.9	1.4	6.9	1.4	0.7
10	0	0	0	0	0	0	0	0	0	0	0	0
L = 90 nmi												
0	50.6	10.1	5.1	24.9	5.0	2.5	16.3	3.3	1.6	7.9	1.6	0.8
1	43.7	8.7	4.4	21.4	4.3	2.1	14.0	2.8	1.4	6.7	1.3	0.7
3.3	27.7	5.5	2.8	13.4	2.7	1.3	8.6	1.7	0.9	3.9	0.8	0.4
10	0	0	0	0	0	0	0	0	0	0	0	0
L = 60 nmi												
0	33.4	6.7	3.3	16.3	3.3	1.6	10.6	2.1	1.1	4.9	1.0	0.5
1	26.5	5.3	2.7	12.8	2.6	1.3	8.2	1.6	0.8	3.7	0.7	0.4
3.3	10.5	2.1	1.0	4.7	0.9	0.5	2.8	0.6	0.3	0.9	0.2	0.1
10	0	0	0	0	0	0	0	0	0	0	0	0
L = 30 nmi												
0	16.2	3.2	1.6	7.6	1.5	0.8	4.7	1.0	0.5	1.9	0.4	0.2
1	9.3	1.9	0.9	4.2	0.8	0.4	2.4	0.5	0.2	0.7	0.1	0.1
3.3	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0

Table 8. Surveillance Fix Rates, SST's

t_{2_n}, maximum allowable interval (in minutes) between fixes to obtain ≥n observations during a crossing of the surveillance zone (supersonic aircraft, V = 1800 K)

ε / σ	5°			10°			15°			30°		
	n = 1	n = 5	n = 10	n = 1	n = 5	n = 10	n = 1	n = 5	n = 10	n = 1	n = 5	n = 10
L = 120 nmi												
0	21.[illegible]	4.4	2.2	10.5	2.1	1.0	6.6	1.3	0.7	2.8	0.6	0.3
1	13.6	3.9	2.0	9.3	1.9	0.9	5.9	1.2	0.6	2.4	0.5	0.3
3.3	14.3	2.9	1.4	6.6	1.3	0.6	4.1	0.8	0.4	1.5	0.3	0.2
10	0	0	0	0	0	0	0	0	0	0	0	0
L = 90 nmi												
0	16.2	3.2	1.6	7.6	1.5	0.8	4.7	0.9	0.5	1.8	0.4	0.2
1	13.9	2.8	1.4	6.4	1.3	0.6	3.9	0.8	0.4	1.4	0.3	0.1
3.3	8.5	1.7	0.9	3.7	0.7	0.4	2.1	0.4	0.2	0.5	0.1	0
10	0	0	0	0	0	0	0	0	0	0	0	0
L = 60 nmi												
0	10.5	2.1	1.0	4.7	0.9	0.5	2.8	0.6	0.3	0.8	0.2	0.1
1	8.2	1.6	0.8	3.6	0.7	0.4	2.0	0.4	0.2	0.4	0.1	0
3.3	2.8	0.6	0.3	0.9	0.2	0.1	0.2	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
L = 30 nmi												
0	4.7	0.9	0.5	1.8	0.4	0.2	0.8	0.2	0.1	0	0	0
1	2.4	0.5	0.2	0.7	0.1	0.1	0.1	0	0	0	0	0
3.3	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0

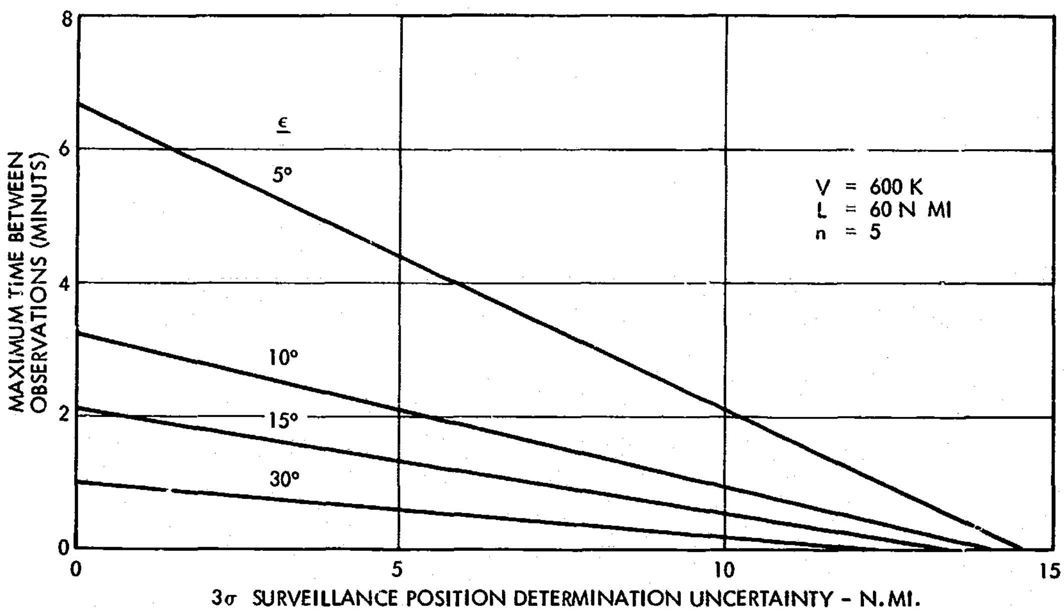


Figure 4. Maximum Allowable Observation Intervals for Subsonic Aircraft Versus Surveillance Accuracy for Various Heading Errors

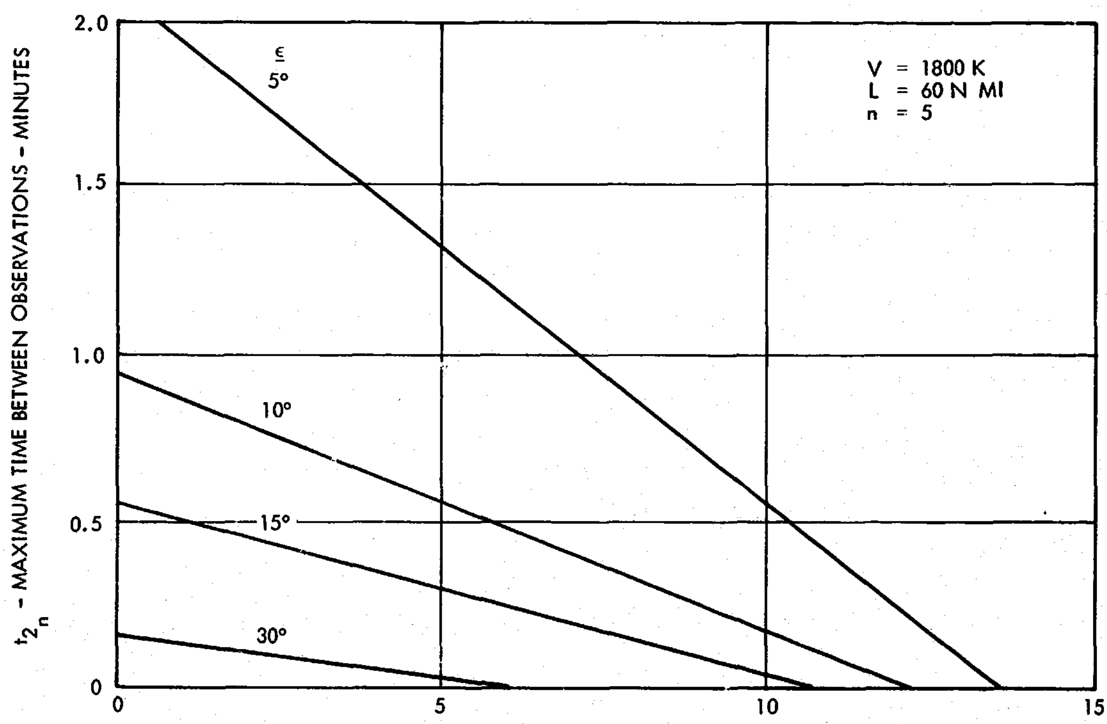


Figure 5. Maximum Allowable Observation Intervals for Supersonic Aircraft Versus Surveillance Accuracy for Various Heading Errors

If it can be assumed that the worst-case blunder that the system can be designed to handle is in the neighborhood of 5 degrees, then it is clear that neither high accuracy or high quantities of fixed rates will be required. This simply says the obvious—that if the aircraft are extremely well behaved, no surveillance is required at all. If the Navigation/Traffic Control Satellite System is used only as a surveillance tool, and if the various aircraft are not allowed to navigate using this system, it is by no means clear that all aircraft will maintain track as well as 5 degrees. There will probably still be a number of used transport aircraft using old (1968) navigation methods. Therefore, as indicated in Paragraph 2.4.3.3, a protection against blunder errors in the neighborhood of 15 degrees was selected. From Figure 7, it can be seen that the reductions in position uncertainty below $\sigma = 1$ do not materially reduce the required surveillance fix load. The design point selected for the navigation traffic control system then is:

$$\sigma = 1 \text{ nmi}$$

$$F_{ntc} = \text{approximately } 11,000 \text{ fixes per hour}^{*}$$

It should be noted that this fix rate will allow at least one observation and almost always two observations on a supersonic transport "blunder" of 30 degrees. Figure 7 also shows that a 1σ position uncertainty of greater than three miles will saturate the system.

There are two trends which will act against each other and will tend to keep the total Navigation/Traffic Control Satellite System surveillance fix load relatively constant. They are:

- Increasing population of aircraft in the North Atlantic Ocean area, and in fact in all areas of the world.
- Increasing accuracy and reliability of navigation of these aircraft, therefore, permitting a lower design value of the blunder error, ϵ.

---

*A fix interval of 20 seconds for supersonic and 80 seconds for subsonic aircraft yields a total of 11,250 fixes per hour, and uses some 73 percent of capacity of a 1200 bit per second data channel.

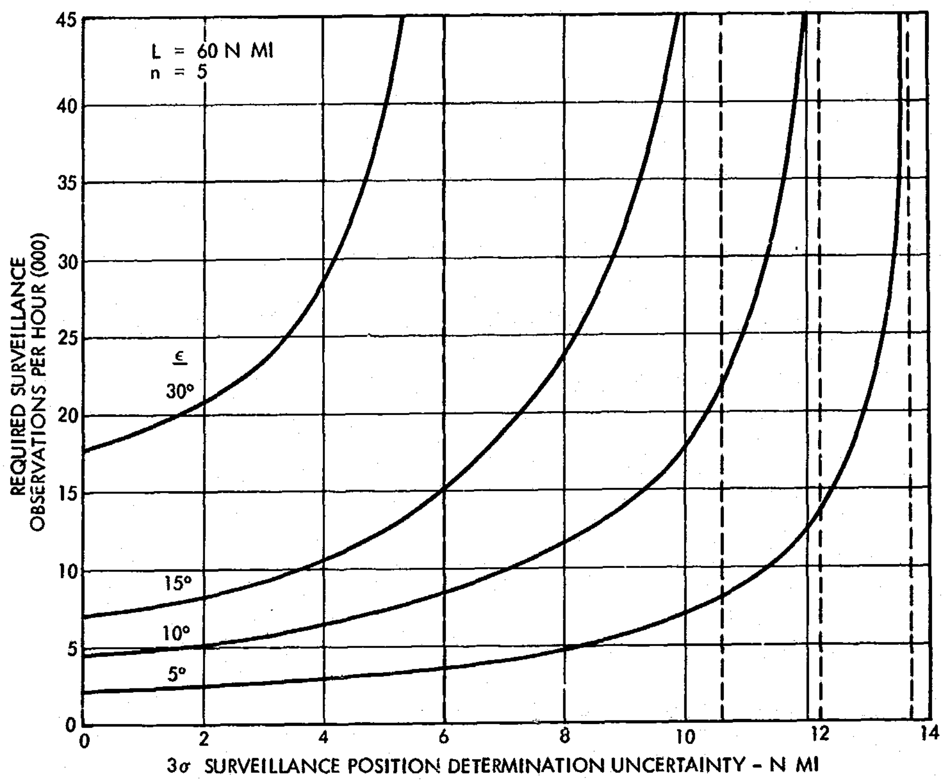


Figure 6. Surveillance Accuracy Versus Fix Rate for Various Heading Errors

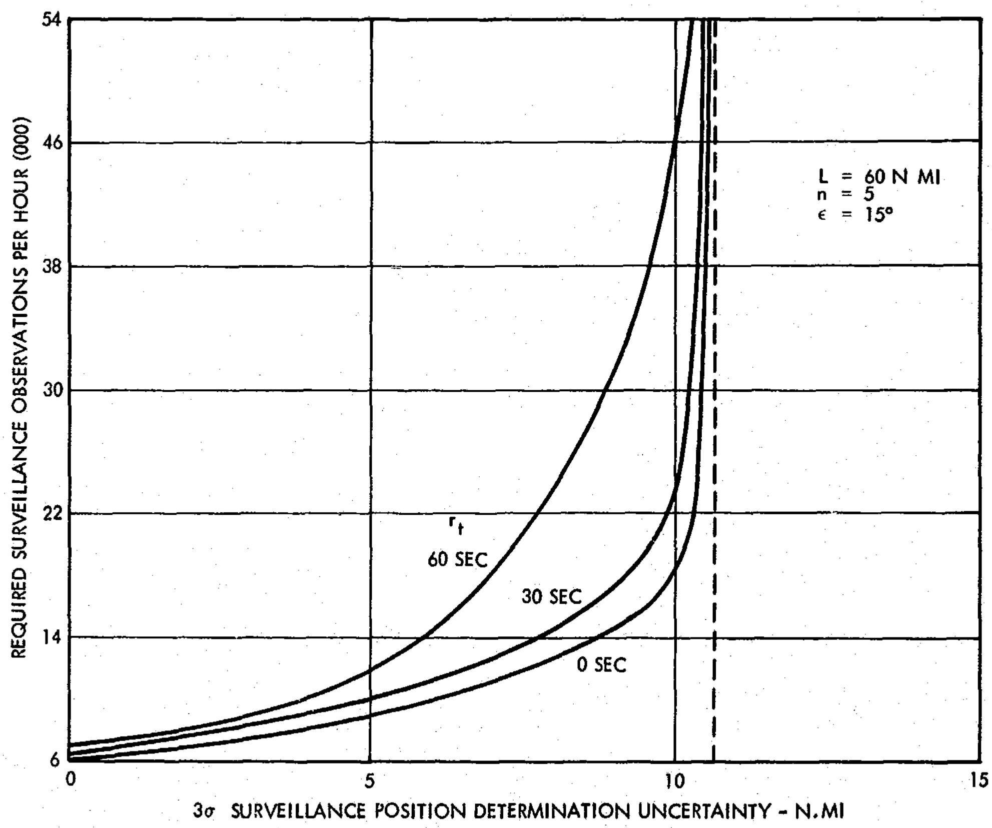


Figure 7. Effects of Reaction Time, r_t, on Total Number of Surveillance Observation Required Per Hour

For example, if over a period of 10 years it was demonstrated that the design blunder error figure could be reduced from 15 to 7 degrees, but at the same time the population doubled, then the required number of surveillance fixes per hour would remain essentially constant. This points out the desirability of using this system to provide a credible source of accurate navigation/track keeping data of the user craft in a way which can provide precisely the type of information required to reduce separation standards in the North Atlantic Ocean area. This point will be discussed further in a later paragraph on growth potential.

2.4.4.3 Reaction Time

Clearly, if the one minute system and crew reaction could be eliminated then for the n = 5 case, an extra 12 seconds could be allowed between each observation in order to insure that five observations were made during a transit of the surveillance zone. It can be seen from Figure 7 that the fix rate reduction which would result is only modest, i.e., from approximately 9000 to approximately 7500. Therefore, one could not, on the basis of reducing surveillance or lateral separation requirements, introduce new communications or displays for the purpose of handling airspace violation warnings or commands.

2.4.4.4 System Growth and Growth Potential

The only thing certain about the air traffic control picture in the last quarter of the twentieth century in the North Atlantic Ocean area is that it will change. Uncertainties in trends in world population, revenue passenger miles, the mix of aircraft between supersonic transports and subsonic jumbo jets, the degree to which travelers would accept inconvenient departure/arrival times in order to alleviate conjestion, as well as the performance characteristics of all systems relating to aeronautical and nautical operational and support services—all of these uncertainties make predicting the needs of the system in 1980 or 1985 very difficult. The system itself, however, can provide some of the answers and point out the direction of its own growth, because the Navigation Traffic Control System generates, in usable form, the very data required to evaluate separation standards, standard operating procedures, and the like.

As indicated in Table 9 (which is adapted from Reference 13), evaluation of deviations which involve disclosure of information and could be at minimum embarrassing and possibly quite costly to an air carrier is not without controversy.

Table 9. Typical Large Track-Keeping Deviations and Operator Comments (Reference 13)

Case No.	Observed Deviation	Comments
1	102.7 nmi South	Form 1-D* stated deviation 33 nmi South Reason given: poor heading control
2	63.7 nmi South	Company regretted that documentation was missing and Form 1-D could not be submitted
3	62.2 nmi South	Form 1-D states no deviation over 30 nmi
4	64.7 nmi South	Form 1-D states no deviation over 30 nmi
5	63.8 nmi South	Form 1-D states no deviation over 30 nmi
6	56.8 nmi South	A Form 1-D was received but was found to be for another flight The company wrote to say that this flight experienced a period of navigational difficulty in the vicinity of 33 W and that inspection of the navigational chart indicated that the aircraft was probably about 30 nmi South of track while within range of weather ship "Charlie." They also stated that the deviation would be as high as 65-70 nmi.

It was predicted in Reference 14 that the lateral separations in the North Atlantic would by the end of 1968 be reduced to 90 nmi. This reduction did not take place, partially because of limitations in track-keeping ability of today's aircraft to a large extent; but to a large extent it appears to be the result of insufficient confidence in the surveillance data available. The Navigation/Traffic Control Satellite System should be configured not only to perform operational surveillance, but also to better supply the answers needed to perform the mathematical and technical separation criteria analyses, the operation analyses leading to standard operating procedures, and the ensuing international agreements.

2.5 AERONAUTICAL NAVIGATION AND COLLISION AVOIDANCE

2.5.1 General

As stated in Paragraph IIB, Objective of the Mission Study Contract (Reference 2), the Navigation/Traffic Control System is to provide for the following position determination functions:

- Aircraft independent position determination for air traffic control and separation assurance
- Aircraft and marine navigation
- Aid to collision avoidance.

In addition, the contractor guidelines in the contract also state that:

> "Air traffic control data derived by the system should be independent of aircraft on-board navigation instruments and processes."

The dual requirement that 1) the system be able to perform multiple functions, and yet 2) these multiple functions be independent of one another, posed one of the most interesting questions raised during the study. For this reason, it is logical to discuss briefly the philosophy of independence of position determination for these various functions prior to stating the navigation traffic control satellite system requirements in this area.

2.5.2 Independent Position Determination

The statement from the contractor guidelines referred to in the last paragraph is quite typical of the aviation community feelings on independent sensors for navigation and surveillance. This feeling is one which has developed over a number of years. As pointed out by Wolinsky (Reference 15), air traffic control was for years based on the flight plans of all flights availing themselves of this control. Flight plans were normally submitted prior to takeoffs, but could also be submitted by existing flights requesting flight plan changes or proceeding without ground control and deciding to enter the control system. The flight plans formed the basis of computation of the flight schedules. The latter were revised, if necessary, on the basis of the periodic position reports of the pilots. The latest information available formed the basis of the recomputation of the schedules of the further portions of the flights. The flight schedules, in turn, were the basis of the conflict searches which were continually made by the ground controllers or by any ground control equipment. The discovery of a future conflict situation resulted in remedial action ordered by the ground controllers.

The periodic position reports of the pilots thus formed an essential part of the conflict search. A position report contained the aircraft's identity, its position, the time of the report, aircraft altitude, and other details such as weather data which was of interest to the ground controllers. Position, altitude, and time were — with projected aircraft ground speed — the data on which the further projection of a flight was based. Obviously, an error in position was perpetuated in the projection of the flight. This results in a margin of uncertainty within which the aircraft must be assumed over the various portions of the remainder of the flight. For an error of a given magnitude in position, this margin of uncertainty grows linearly with the speed of the aircraft.

Furthermore, these periodic position reports were of necessity transmitted when the pilot was free enough of other duties to make the verbal call-up and when he was able to get on a channel. Both of these factors led to substantial delays in reporting. The form in which this information was available to the controller was a slip of paper with penciled information taken via voice link from the pilot. It is not difficult to visualize a busy controller attempting to keep up with a lot of aviation traffic for which he was responsible with a series of slips of paper. Obviously the situation was an invitation to significant human error and therefore, a great deal of conversatism was introduced to the system, resulting in very high separation standards and thousands of cubic miles of wasted air space.

Again, from Wolinsky (Reference 16): "in 1960, the FAA instituted an experiment called 'Operation Pathfinder,' in which enroute air traffic was for the first time observed on radar. This experiment lasted six months and was carried out in the Chicago - Minneapolis area. Ground controllers maintained enroute air traffic control and issued instructions to the pilots based on their visual observations. As was to be expected, the experiment was an unqualified success. Being able to observe developing conflict situations on the radar screen, the controllers were able to judge (in many cases in which automated air traffic control would have required a change in at least one of the flight plans involved) that, with continuing observation of all flights, the flights could be allowed to proceed without change and without compromise of safety. In other cases, slight deviations of one flight plan sufficed for the resolution of the developing conflict situation. Thus, the actual number as well as the extent of the necessary interferences with the flight plans by the controllers in the 'Operation Pathfinder' was only a small fraction of that which would have been necessary without direct radar surveillance of air traffic.

"This result was not surprising. Air traffic control as practiced then, with or without computer assistance, was based on the computed traffic situation as it would prevail in an area in the coming half hour, approximately. The computation of this situation was based on the various submitted flight plans and on their updatings made while the flights were in progress. Without computer assistance, the computations were made mentally by the ground controllers who used their mental picture of the airways of their sectors and the flight information contained on the flight progress strips. With automation, the computations were to be made by the computer on the basis of the same information which was to be stored in its memory. In either case, in the absence of direct surveillance of the enroute air traffic, the FAA required a 10-minute time separation of two aircraft crossing any ground point at the same altitude, and corresponding separations of aircraft, flying at the same altitude, whose paths did not actually cross but approached each other to a distance which could be covered in less than 10 minutes. Such separations, while necessary for the observance of the prescribed safety standards, required, due to the high speeds of modern airplanes, the maintenance of large empty air spaces between flights of equal altitudes. Consequently, the number of conflict situations, which are instances of violations of the prescribed separation standards, was relatively high. The resolution of such conflict situations was normally accomplished by an altitude change of one of the flights, or, if no traffic-free neighboring altitudes were available, by the marking of time of one of the flights, flying a certain segment back and forth, or, if approaching air traffic made this impossible, by the diversion of one of the flights from its flight path. Such diversions would frequently be made along crossing airways, thus taking the affected flight considerably out of its intended course. Frequently, such changes created conflict situations with third and fourth flight plans which would then have to be changed, in turn. Thus, the resolution of the conflict situations between two flight plans frequently reverberated into a number of other flight plans, particularly in high-density traffic areas.

"The visual observation of the enroute air traffic in the 'Operation Pathfinder,' on the other hand, enabled the controllers, who were able to observe aircraft closely through any developing and resolving conflict situation, to reduce drastically the minimum separation standards. Thus, in most cases, actual changes of flight plans could be avoided or, if this was not possible, the extent of the changes could be kept much smaller than was allowable without visual observation. This, as well as the very significant decrease in the number and the extent of the reverberations of flight plan changes into other flight plans in the area, contributed greatly to the maintenance of a smooth air traffic.

"It was no surprise then that, at the end of the experiment 'Operation Pathfinder,' the controllers were not only highly enthused with the results of direct radar observation of enroute air traffic,* but were also critical of the role of the computer. Prior to 'Operation Pathfinder,' the controllers favored strongly the idea of the computer which, in the absence of direct air traffic observation, would relieve them largely of the burden of the maintenance of a mental picture of the present, and the computation of a mental picture of the future, air traffic in their sectors. Also, the controllers felt that, in the presence of radar observation of air traffic, any notification by the computer of developing future conflict situations would only be distracting and that they would much rather concentrate on the observation of the radar screen."

*Perhaps what the operators really liked was the visual display provided on the radar screen. Had telemetered data been projected in a similar fashion onto a screen, and if such displayed information proved to be reliable and accurate, the operators may well have been just as enthusiastic. The critical elements, of course, are reliability and accuracy.

Summarizing then, there are a number of reasons why independent position determination for surveillance seems desirable:

- Position reporting via voice channel poses a heavy load on air crews, ground operations, and inadequate communication channels
- Position reports are often inaccurate
- There are significant lags introduced in the reporting procedure by the air crews, and in the interpretation of the data by the ground crews
- The format of the information has been poor, not providing the traffic controller with an immediate and continuous mental picture of the air traffic situation
- If a single sensor system is used for surveillance, then all aircraft will be on the same grid, and their relative positions will be well established, certainly much more so than if the various aircraft indicated positions were based on VOR, inertial, visual, and dead reckoning methods
- Finally, the air crews themselves are comfortable knowing that there is an independent navigation system available to them in an emergency. If required, a ground controller can actually navigate for the pilot giving him steering instructions and "bringing him home" during critical or emergency flight conditions.

Reliability of both people and equipment suffers when they go up in an airplane. Therefore many would insist that surveillance information be completely independent of all aircraft systems; while others would be satisfied simply to keep the air crews out of the loop. The point in question, however, is how to maximize the reliability of the total aircraft-plus-air-traffic-control system, and if it could be shown that redundancy of similar systems rather than redundancy through totally different systems could, in fact, provide a higher probability of success in terms of safety of air travel, then some measure of independence may well be sacrificed. During the course of the study, NASA and TRW jointly agreed that the automatic reporting of navigation satellite data for surveillance (as long as this data was not processed by an airborne navigation computer) would satisfy the independent position determination requirement. (This scheme, called AUTOREP, is described in Reference 17 and elsewhere in this report.)

One question remains open and cannot be resolved at this time. That is: 1) "Would it be better for an aircraft to navigate with the NTCS as its primary sensor using doppler, inertial navigation, or some other sensor system as a check in the backup? Or, 2) would it be better to have the primary mode of navigation be, say, inertial using navigation satellite data only in an emergency? 3) Or would it be better to withhold from the aircraft the ability to navigate with the navigation satellite data at all?" Most of the aviation community appears to be divided between the latter two approaches, while TRW favors the former. As pointed out by Philco in Reference 4, good relative position information is far preferable for surveillance since the primary purpose is to assure separation of aircraft from each other. The advantage of this difference between relative position and absolute position may be more virtual than real, however, if the aircraft themselves cannot navigate and track-keep on the same grid. If an air traffic controller wants to squeeze aircraft close together he must know that they will adhere closely to a predictable, presumably assigned track. A good example of this can be seen at the Los Angeles Center FAA Facility in Palmdale, California wherein an air traffic controller is monitoring a large number of aircraft coming into Los Angeles airport late in the afternoon. These aircraft are indeed flying on the same grid, namely the Los Angeles Airport Instrument Landing System (ILS). If these aircraft were all navigating using different techniques and on different grids it is unlikely that they could be squeezed so closely together even though they were all aiming for the same point. The air traffic controller cannot fly the aircraft for the pilots; nor can he even "vector" (using voice commands) more than one or two aircraft and still do an adequate job of monitoring the performance of the rest. Aircraft must be able to fly on his grid, but without his continued intervention or help.

The desire for a completely independent sensor system for the collision avoidance system (CAS) is again based on the judgment that a CAS would not in fact be a backup device if it were an integral part of the air traffic control or aircraft navigation system. Again, the same arguments on reliability and redundancy would apply here.

In summary:

- The strong desire on the part of the aviation community for independence of position determination is overriding
- The order of priorities for the three position determination tasks for the NTCS are:
  1) Surveillance
  2) Navigation, and
  3) Collision avoidance.

∴ The Navigation/Traffic Control Satellite System will be configured such that the surveillance function will be performed and the other two functions may be performed as growth items, but no additional capacity requirements will be imposed on the system by these latter two functions.

2.5.3 Navigation/Track-Keeping

From the analysis performed in Paragraph 2.4 relating surveillance accuracy to fix rate requirements, it is also possible to infer that a 1 nmi position determination accuracy for navigation/track-keeping would also suffice. For growth potential into high density over land and terminal area traffic, it is clear that accuracies of well below this figure would be required and accuracies down to, say, 100 feet would be needed for low approach operation. In fact, the utility of the Navigation/Traffic Control System increases monotonically and is a direct function of the position determination accuracies available.

2.5.4 Collision Avoidance/Station-Keeping

In February of 1967, Mr. J. L. Brennan at the Institute of Navigation National Air Meeting on collision avoidance (Reference 18) stated the FAA position as follows:

"We do not intend airborne collision prevention devices to be a substitute for a ground-based air traffic control system, nor do we believe that the ground system should be designed to rely on the airborne devices for separation of aircraft. We believe the best solution to the problem of potential mid-air collisions is a positive, fail-safe air traffic control system under the jurisdiction of a central agency exercising control from ground facilities. The desirable role of an airborne collision prevention device is that of an independent backup to the primary system. Additionally, it should provide protection in areas and to aircraft not serviced by the ATC system."

Accordingly, the FAA has concentrated almost exclusively on their air traffic control responsibilities, but they are looking beyond their immediate needs and methods of implementation. Blatt has pointed out (Reference 19) that:

"Currently, most of FAA's resources are going into automation programs to enhance the air traffic control capability both in the enroute and terminal areas. In the main, this consists of providing an automatic data acquisition, processing and display system for the assistance of the air traffic controllers, thus improving the effectiveness of the modus operandi. Though it involves large expenditures, utilizes techniques and components that represent the best of the leading edge of the state of the art and promises definite benefits, it must be recognized as merely patching the present system. Functionally, nothing really new is being added. The controller's fundamental responsibility and mode of operation will not change materially. The end result will be that he will still exercise complete control of each individual aircraft under his jurisdiction, and be solely responsible (under instrument flight rules conditions) for separating each aircraft from all others.

"Through software updating, hardware reconfigurations, and procedural changes, an automated air traffic control system using existing control philosophy should meet our forecast needs. However, adding sophisticated equipment and more people on the ground will eventually reach a point of diminishing returns and sooner or later — hopefully much later — we will have to alter our system premises. The dependence on the controller to control each individual aircraft throughout its entire journey from takeoff to landing is the principal limiting factor in the current system. When the state of the art will permit, greater system reliance will then be placed on the pilot's capability of maintaining his own separation from other aircraft under all visibility conditions."

Later in the same talk Mr. Blatt even referred to a "combined collision avoidance, ATC data acquisition, communications, and navigation system" as a possible future approach.

Collision avoidance and station-keeping, then, appear to be very likely growth items for the Navigation/Traffic Control Satellite System. The system therefore must be configured such that it is capable of this growth. Although it was beyond the scope of the Mission Study to perform a detailed collision avoidance requirement accuracy analysis, the following points are clear:

- If assured miss distances on the order of 0.5 nmi are desired, then relative position determination uncertainties on the order of 0.05 nmi are called for.
- The altitude determination process using barometric altimeters, transducing systems, and transmittal of this information appears both inaccurate and awkward.
- Altitude determination uncertainties of greater than approximately 700 feet (3σ) appear unacceptable if vertical maneuvers are to be used. Larger uncertainties can lead to altitude airspace violations.
- A complete update of position must occur somewhat more frequently than is required for surveillance or navigation. A partial update should occur every few seconds and a complete update several times a minute.

2.6 NORTH ATLANTIC MARINE OPERATIONAL SUPPORT

2.6.1 Forecast of Marine Traffic in the North Atlantic Region — 1975

To determine the number of ships in the North Atlantic in 1975, References 10, 20, and 21 were examined. These references contain information which is summarized in Figure 8 on present ship population, estimated growth rate of the world ship population utilization rates (i.e., the percent of time that a ship is in use), and percent of world ships using the Atlantic routes. From this information forecasts of world ship population and marine traffic in the Atlantic region for the 1975 time period were made.

First, the world ship population for 1975 was estimated by using the growth rates and the ship population data associated with each of the three references. These results (shown in Figure 8) indicate a difference of approximately 11 percent in the range of values associated with the high and low estimates. From these results estimates of the number of ships in the Atlantic at any given time in the 1975 time period were obtained. This was accomplished by applying the utilization rates (i.e., the percent of time that a ship is in use) and information pertaining to percentage of ships using the Atlantic routes to the results of Figure 9. This final result (shown in Figure 9) indicates a difference of approximately 50 percent between the high and low estimates.

As is evident from Figures 8 and 9, only ships greater than or equal to 100 gross tons are included in these forecasts. The exclusion of other type vessels was necessary due to the lack of reliable information on them. The forecast presented herein is thought to represent a reasonable, but not necessarily binding, estimate of the number of marine system users for 1975.

Another factor inherent in this forecast is the fact that References 10 and 20 specified the fraction of world ships in the Atlantic Ocean and did not delineate between the North or South Atlantic. Reference 21, however, indicated that only a small fraction of the Atlantic shipping is conducted in the South Atlantic Ocean. Thus, these forecasts represent estimates of North Atlantic ship population for 1975.

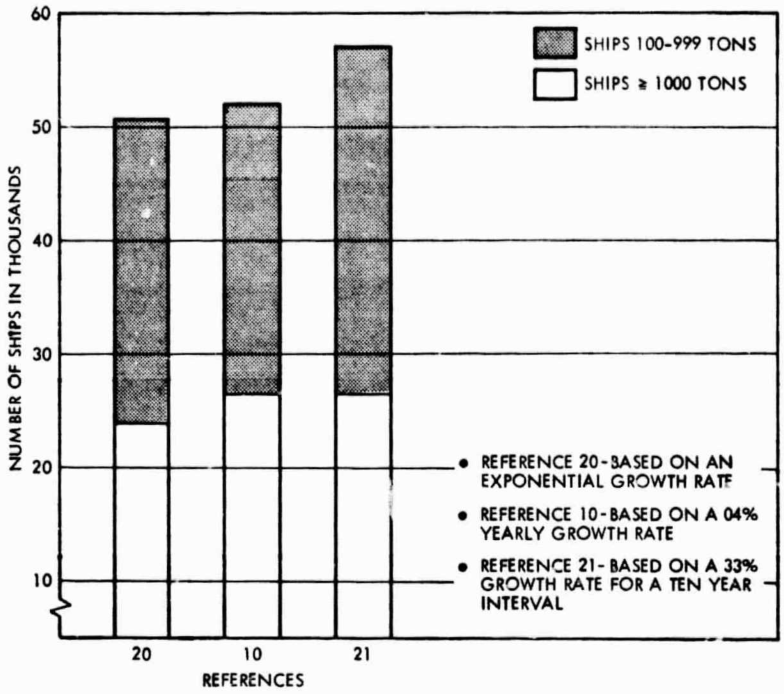


Figure 8. Estimates on World Ship Population ≥ 100 Tons—1975

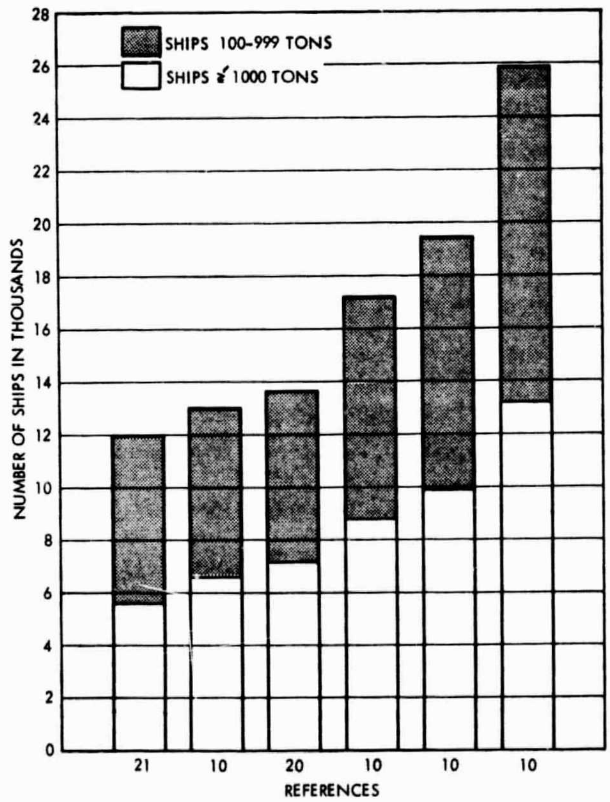


Figure 9. Maximum Number of Commercial Ships ≥ 100 Tons in the Atlantic at any Given Time—1975

After examining Table 10 it was decided that the estimate derived from Reference 20 on the maximum number of ships in the North Atlantic at any given time would be used as the baseline case. This estimate was chosen for two reasons:

(1) The value of 13,500 provided by this reference is close to the median value of the estimates shown in this figure.

(2) Reference 20 was the most detailed and thorough of all the references examined.

Table 10. Summary of Pertinent Parameters Used to Forecast Marine Traffic in the Atlantic Ocean

Refer.	World Ship Population in Thousands	Estimated Growth Rate	Utilization Rate	Percent of Population in Atlantic Ocean
10	18.0 ≥ 1000 tons 17.0 ≥ 100-999 tons (1965)	Annual growth rate - 4%	50% - 75%	50 - 66%
17	17.3 ≥ 1000 tons 19.0 100-999 tons (1960)	Exponential growth where $S = k\,e^{\alpha x}$ S = Forecast for year t k = 1960 estimate α = 0.0223 x = (t-1960)	50% 60%	60% 40%
18	20.0 ≥ 1000 tons (1965)	Growth rate for a ten year interval - 33%	60%	35%

2.6.2 Marine Navigation and Control

2.6.2.1 Background

Ships traditionally navigate international waters at will, guided somewhat by "rules of the road" as agreed to by international convention. In the past the need for precision and frequency of navigational information has depended primarily upon the proximity to harbors, waterways or obstructions, except for special missions such as search and rescue. This operational freedom has resulted in a steadily increasing collision rate, and tonnage losses rose by 150 percent in 1966 (Reference 22). Larger ships experience about 100 potential collisions a year and there were 2320 actual collisions between 1960 and 1966 (Reference 23). The evolving need is for both a reduction in hazard and also an increased ability to define and follow optimum courses. The advent of the fast automated ship and the potential for general employment of the surface effect ships which can cruise as fast as 80 knots create a new class of requirements for safe, expeditious operation (Reference 24).

2.6.2.2 Present Navigational Environment

Celestial navigation is still the mainstay of ship navigation, but its accuracy limitations, weather dependence, and slowness make it suitable only for the open ocean. LORAN and related hyperbolic systems do provide both all weather performance and faster readout, but coverage is not uniform and error patterns vary with the ionosphere so as to be unsuitable for navigation in close quarters. Radar is especially useful in congested coastal regions but radar performance is seriously degraded by precipitation and, furthermore, incipient collision courses are difficult to detect and evaluate when several ships are present. Fixed location harbor surveillance radar such as is used at Southampton and Rotterdam provides useful information, but can be degraded by weather conditions and radar target identity confusion. Collision courses are not obvious from radar displays without track determination and computation.

2.6.2.3 New Navigation Requirements

The increasing incidence of ships colliding and constraints upon operation during limited visibility are becoming more critical with the introduction of high performance vessels. There is an implied need for control of traffic in certain areas that could resemble the objectives of air traffic control for providing safe, expeditious transit along desired routes. This implies the definition of assigned channels or lanes and the provision of a capability for either self-determination or central control of safe separation intervals. The system should provide all-weather operation so as not to delay traffic in low visibility and heavy precipitation conditions. This requirement implicitly includes the use of continuous, high accuracy position determination in the critical control areas and would make use of this equipment mandatory for all ships in the area. Similarly, this type of position information would be needed for those ships operating over optimized tracks which are adapted to environmental conditions. The most critical requirement will exist for surface effect ships whose high cruise speeds present control problems similar to those of aircraft.

2.6.2.4 Navigation/Traffic Control Satellite Contribution

Since the Navigation/Traffic Control Satellite System provides the capability for continuous, worldwide, highly accurate position information and communications services, a new approach to ship navigation and control is feasible. Although the present high collision threat would not be helped materially by navigation improvement alone, continuous, precise position data as indicated by relatively simple shipboard equipment could permit either self-directed or centrally-controlled collision avoidance in areas of high risk. A marine traffic control system could technically be similar to that used for air traffic control.

2.6.3 North Atlantic Marine Requirements

2.6.3.1 Marine Communications

A communications load analysis for North Atlantic marine operations was conducted and is described in detail in Section 3.8 of this volume. This analysis, though similar to the aviation communications load analysis in its approach to the problem, was much less extensive. Typical marine messages were constructed and a communications load accounting for message length and contact rate was estimated. The study was begun with the ground rules, from Reference 2, that there should be no significant delays in the operation of data links between user craft and ground stations, and that when required, information requested by user craft or associated ground stations should be returned and displayed within five seconds. Using this ground rule, a requirement of four 1200 bit/sec data channels at a 30 percent utilization rate resulted. However, it was apparent from the examination of the messages themselves that they were of such a nature as to not require the five-second criterion. As a result, the recommendation is made that for marine communications, two 1200 bit/sec data channels at 60 percent utilization rate plus a third emergency data channel be assigned full time for merchant marine operation in the North Atlantic. Furthermore, during the off-peak aviation hours, it is recommended that an unspecified number of voice channels be allocated to marine use. Limitations in time and the scope of the contract did not allow more detailed study of this allocation but it seems clear that such an allocation would be a useful approach.

Section 6, Applications, of Volume II of this report has a further discussion of potential maritime applications of the Navigation/Traffic Control Satellite System.

2.6.3.2 Marine Surveillance

As indicated in Paragraph 2.6.2, there are a number of indications that the use of marine traffic control systems on the high seas is a very real possibility. Since the North Atlantic Ocean Area — on the sea, as well as in the air — is the most heavily trafficked oceanic area in the world, marine surveillance requirements are postulated here for that area. For example, one marine surveillance approach would call for some 21,200 fixes per day. It is based on two types of surveillance. The first type assumes a 100 percent participation in something like the present American Merchant Vessel Voluntary Reporting (AMVER) System which involves position determination and reporting. Since it is estimated that there will be some 13,600 ships at sea, this would entail that number of position reports per day. This has been factored into the communications load analysis that follows. The position reporting postulated here is not the Autorep system postulated in the aircraft case, although it very well could be. The position reporting technique described in the marine portion of the communications load analysis is simply a teletype version of a voice position report. The reasons that teletype position reports were used rather than Autorep were:

- The Navigation/Traffic Control Satellite user hardware equipment for ships may well be of the less expensive variety, not lending itself well to the Autorep technique.

- The teletype position report can be rendered by ships using navigation methods other than the Navigation/ Traffic Control Satellite. Since retrofit in the marine situation may well be much slower than in the aviation community this approach seemed advisable.

- The communications requirements using the position report are slightly longer than Autorep, rendering the requirements analysis slightly conservative in this regard (e.g., 232 bits for a position report versus 200 bits for an Autorep message).

Second, some 7600 fixes would be required by a more positive form of marine traffic control, which, it is postulated, would take place when ships were within some specified range of one another. As pointed out in Reference 23, the average ship encounters 100 collision situations per year. For this criteria, this number has been degraded by a factor of 50 since this analysis deals primarily with open ocean operation. The resultant probability of collision situation encounter is multiplied by the population and again by an assumed 100 fixes per collision situation per ship, resulting in the 7600 fix figure. Obviously this figure could be reduced if the traffic controller directed ships to change their course fairly early in the encounter situation but from an operational point of view, it is probably cheaper to take more position determination fixes and allow the ships to remain on course for longer periods. In most cases they would probably not be required to maneuver at all. This second form of maritime surveillance is considered more hypothetical at this time, and has not been factored into the communications load analysis as a firm system requirement.

2.6.3.3 Marine Navigation

Possible uses of the Navigation/Traffic Control Satellite System in the North Atlantic could require on the order of 36,820 fixes per day. This is based on three assumptions. First, approximately one percent of the large merchant vessels will have some form of fully automatic shipboard steering which will require relatively high data rates (one per minute) for stable operation. Second, ten percent of the marine population will have some semiautomatic or automatic shipboard navigation wherein fixes are made relatively frequently (one fix per hour) followed by correction of course, and another open-loop autopilot leg of approximately one hour before the next fix. Third, the remaining 89 percent of the population is assumed to take an NTCS fix approximately once a day using manual, less expensive, and possibly less accurate equipment.

2.7 SEARCH AND RESCUE

2.7.1 General

In considering the merits of a search and rescue system or the application of a system such as the Navigation/Traffic Control Satellite System to United States or worldwide search and rescue operations, it is necessary to evaluate not only the benefits in terms of saving of human life, and recovery of material wealth; but it is also necessary to evaluate the cost of the search and rescue operation itself. In an operational sense, during a disaster such as an aircraft down in the Pacific Ocean near Los Angeles, a mine explosion, or the Andrea Dorea marine collision disaster, it is easy to recall that saving of human life predominated in the operational phase. Those responsible for the rescue operations wanted to do the best job possible, as fast as possible, in order to maximize the saving of human life. Only when the rescue operation itself becomes dangerous, e.g., in a mining disaster or when the chances of rescue become extremely remote does the operational rescue commander start to "balance the books" in his own mind. However, costs are a more significant factor during the research and development phase and when executive or legislative agencies of the government are deciding what operational tools to place in the hands of the search and rescue commander. It is here that such cold decisions must be made, and it is in that light that recommended search and rescue capabilities with regard to the Navigation/Traffic Control Satellite System are discussed.

Time and dollar limitations on this study have prevented any economic benefit on search and rescue but the following should provoke a general feel for the "balance" (from Reference 25):

- In 1964 there were 2308 casualties at sea involving 3178 vessels. Of these 390 vessels were totally lost, 191 died, and 133 were injured. These losses were caused by collisions, explosions, fire, material failure, drowning, weather, navigation error, personnel error, and totaled $68, 355, 000.

- The search for a single aircraft downed in the Pacific in 1964 cost well over $1,000,000. Estimates have been made which indicate that over 27,000 search and rescue hours have been flown by the Air Force, Coast Guard, and Navy during a 12-month period.

2.7.2 Study Inputs

The following criteria are taken directly from the Ad Hoc Joint Navigation Satellite Committee Final Report:

"General

a) The systems of navigation and communication must be in common use by the marine and air interests of the United States and other nations.

b) The system must be capable of evolutionary implementation and expansion.

c) Facilities and services must be available 24 hours per day.

d) Navigational system must be available to all users simultaneously.

Specific

a) Navigation: It is desirable that the system indicates present position on a chart automatically and provides additional readout of course, ground speed, distance to go, angle and distance to track for both air and marine use.

b) Communication: The system should:

- Provide communications for operational control from base and on-scene.

- Provide communications for interchange of position and weather information over both long and short distances.

Detailed Search and Rescue Requirements:

- Navigation: 1975 absolute: one mile at ten minute intervals worldwide; relative: 1000 feet continuous within areas of primary Coast Guard responsibility; 1000 yard worldwide.

- Communications: Three-voice channels, worldwide, less polar regions."

2.7.3 Recommended NTCS Search and Rescue Capability

It is recommended that one or two aircraft voice channels be allocated on a preempting basis to search and rescue operations. This recommendation falls short of a full-time assignment, but on this basis more than three channels could be made available to worldwide SAR operations. Furthermore, a full-time emergency voice channel is available for aircraft at all times and a full-time emergency data channel is available to marine craft at all times. Thus, at the outset of an emergency, the alarm can be triggered on an immediate basis. The air traffic control agency can immediately be notified and also immediately assign empty channels or vacate and reassign channels for the search and rescue operation. It is not at all unusual for a traffic control agency to call a pilot and tell him to monitor a new frequency. Thus it is quite practical and reasonable to expect that this air traffic control agency could broadcast to all aircraft on a particular channel or frequency, which is to be reassigned to the search and rescue operations, that those aircraft should leave this frequency and go to a new assigned frequency. To increase reliability, if necessary, such information could also be simultaneously broadcast on data link to the aircraft digital equipment. Thus it is estimated that channels in use could be completely vacated within several minutes. This is a great deal faster than a large search and rescue operation can be mounted and in operation to the degree that would require full-time use of these channels. Thus it appears unlikely that this preempt basis assignment of channels to search and rescue would be a pacing factor or an unsatisfactory situation for the search and rescue commander. With regard to position determination, it is seen that the accuracy requirements for search and rescue for absolute accuracies are similar to those required for air traffic control, but that the relative accuracy requirements are somewhat more stringent. It would be considered very desirable if the Navigation/Traffic Control Satellite System could meet these accuracy requirements.

2.8 MARINE SCIENTIFIC

2.8.1 Study Inputs

The following criteria are taken directly from the Ad Hoc Joint Navigation Satellite Committee Final Report:

"1. General Criteria

a. A system open to all users.

b. Size of user equipment must be "reasonable," i.e., about the size of a shipboard radar.

c. Ease in maintenance and dependability of operation of user equipment is important. Modular construction is recommended.

d. Ease of operation is a consideration.

e. The system must be operational 24 hours a day; it should be available in excess of 95 percent of the time, and down time for periodic maintenance should be rigidly scheduled well in advance.

f. Cost of user equipment is a consideration.

g. Automatic plot, and autopilot-type information would be useful but is not essential for this class of user.

2. Specific Criteria — apply to most research, survey, and specialized commercial vessels:

a. Position Determination

(1) Position determination on a real time basis. Fix intervals of 10 minutes, or on demand.

(2) Fix precision and accuracy of $\pm$ 0.05 nmi. These rigid requirements arise both from the need to locate the sites of oceanographic observations and from the need for a precise determination of speed and course over the ground, which are necessary to compute corrections to gravitational acceleration measurements under way.

(3) Worldwide (except polar) all-weather coverage.

(4) Position determinations must be free of ambiguity.

b. Communications

(1) There is a need to provide dependable communication facilities on a worldwide basis.

(2) There is no requirement for traffic control.

(3) Search and rescue requirements are essentially the same as for other vessels."

2.8.2 Discussion

The only specific criterion listed above which exceeds any of those previously discussed is the 0.05 nmi position determination accuracy requirement. For purposes of evaluating the Navigation/Traffic Control Satellite System design, this "requirement" will be downgraded to a "desirable" feature. Marine scientific craft and certain other marine applications will be considered, not as primary users about which the system will be designed, but instead as additional or special "applications" to which the system should cater in order to get a broad subscriber or customer base. Further marine applications of the Navigation/Traffic Control Satellite System are therefore discussed in Section 6 of Volume II.

2.9 REFERENCES

1. N. Braverman, "Separation Assurance Over the North Atlantic," Paper presented at the 24th Annual Meeting of the Institute of Navigation, Monterey, California, 21 June 1968.

2. "Navigation/Traffic Control Satellite Mission Study," NASA/ERC Contract No. NAS 12-595, 1 December 1967.

3. N. E. Halaby, "All-Weather Operations – Progress and Challenges," in Astronautics and Aeronautics, May 1968.

4. "Systems Engineering Study of Aeronautical Satellite Services," Volume II, Philco Document No. TR-DA1583(1), 15 December 1967.

5. M. W. Cardullo, "Oceanic Air Traffic Projections, 1966-1976," ComSat Technical Memorandum No. SAD 167.

6. C. E. Dunmire, "North Atlantic Air Traffic Activity During the 1975-1980 Time Period," FAA Technical Note, Project No. 197-622-02R, June 1966.

7. J. S. Mays, "An Analysis of the North Atlantic Principal Area Separation Standard and Communications Problems for the Present to 1980 Time Period," FAA Working Paper, Project No. 221-160-01C, August 1966.

8. "Advanced SST Guidance and Navigation Systems," Final Report, TRW No. 08237-6011-R000, Volume II: Supporting Analysis, 30 April 1967.

9. "Project Dioscures Systems de Controlle et de Navigation Aerienne Por Satellites, Application a l'Atlantique Nord," Centre National D'Etudes Spatiales, 1967.

10. L. Jaffe (NASA), et al, "Final Report of the Ad Hoc Joint Navigation Satellite Committee," 13 May 1966.

11. S. Poritsky, "Anticipated SST Airline User Problems," in Proceedings of the ION National Air Meeting on Supersonic Navigation - Now and Tomorrow," Seattle, Washington, 15-16 November 1967.

12. C. E. Dunmire, "Math Model of the ATC Surveillance Process," Unpublished notes, obtained 11 October 1968.

13. "Summary of Discussions of the Fourth Meeting of the North Atlantic Systems Planning Group (NATSPG)," Paris, 17-28 June 1968.

14. D. Manis, "SST Navigation," in Proceedings of the ION National Air Meeting on Supersonic Navigation - Now and Tomorrow, Seattle, Washington, 15-16 November 1967.

15. A. Wolinsky, "Improvement of Air Traffic Control," (TRW Notes) approximate date August 1965.

16. A. Wolinsky, "Automation of Air Traffic Control Aspects and History," TRW Document No. 9322.9-256, 18 August 1965.

17. "Study of a Navigation and Traffic Control Technique Employing Satellites," Volume 1: Summary, TRW Report No. 08710-6012-R000, December 1967.

18. J. L. Brennan, "Status — Airborne Collision Avoidance System Program," in Proceedings of the ION National Air Meeting on Collision Avoidance, Dayton, Ohio, 23-24 February 1967.

19. J. D. Blatt, "The National Airspace System — Its Future Growth," speech given at Fort Monmouth, N. J. — US Army Electronics Command on 6 March 1968.

20. J. W. Campbell, Technology Audit Corporation, "Predicted Operation Requirements for a Non-Military Traffic Coordination and Navigation Satellite System," (Final Report).

21. D. Czubiak, "Strat-X (Search Radar)," TRW Document No. 08810-6002-R300, 15 May 1967.

22. "Practical Aspects of Merchant Marine Navigation," in NAVIGATION, Journal of the ION, Spring 1968.

23. R. F. Riggs, "A Short Study of Statistics of Collisions Between Merchant Vessels," in NAVIGATION, Journal of the ION, Autumn 1965.

24. J. W. Anderson, "Ship Routing in Congested Areas," in NAVIGATION, Journal of the ION, Fall 1967.

3. COMMUNICATIONS LOAD ANALYSIS

3.1 INTRODUCTION

The purpose of the communications load analysis is to examine expected aircraft and marine communications requirements of the Navigation/Traffic Control Satellite System and to relate these requirements to other system design considerations. Of primary concern is the determination of the number of voice and digital communication channels required to achieve desired system performance. Included in this section is a description of the queuing model used for this purpose, and an aircraft and marine message analysis consisting of message classification, message length estimation and an estimate of the expected contact rate between the various elements of the system. The results of these analyses are then used in conjunction with the model in a preliminary evaluation of the expected air and marine communications loads in the North Atlantic region. These results include comparisons of digital and voice transmission channel requirements, as well as an analysis of the impact of variations in message length, message arrival rate, message transmission rate, and aircraft and marine population upon the number of communication channels required for good system performance. The results of the preliminary evaluation of aircraft requirements were then reconciled with the communications subsystem and modified requirements and criteria analyses. The resulting refined estimates of aircraft requirements are presented in Section 3.7, and were summarized in Table 4, page 25.

3.2 COMMUNICATIONS MODEL

Communications between an aircraft or marine vehicle and a ground station via satellite involves the flow of information between the two communicating bodies. For the 1975 to 1985 time period this flow of information will be between many aircraft, marine vehicles and the ground stations via a relatively small number of satellites; hence, it is reasonable to assume that the satellites will be the critical node in this communication network.

Problems involving flow are normally classified according to whether the flow is steady or unsteady. Steady flow in this context means that the messages arrive at the satellite at uniformly spaced intervals of time and that the demands on each channel are the same for each arrival. Clearly this case does not adequately describe the flow of information between aircraft, marine vehicles and various controlling agencies on the ground. For example, some aircraft in the North Atlantic corridor might be in a situation where they would want to report unfavorable weather conditions, while other aircraft might be at a place where they are required to report their position. (Present regulations require that aircraft make a position report every ten degrees.) The ground station, on the other hand, might want to report ARTC information to certain aircraft and not to others; hence, the arrival rate of messages at the satellites will be random in time rather than uniform. Since the length of each message is also variable, the demand placed upon the communication channels by the messages is variable and over relatively short time intervals (say, 30 minutes) can be assumed to be a random quantity; hence, the communication network under consideration is one which deals with unsteady or stochastic flow.

One of the most important features of stochastic communication systems (systems which deal with unsteady flow) is that a queue of messages often forms at a channel even though the average flow rate does not exceed the capacity of the channel. If the flow is steady, then it is sufficient to design the communication facility to handle average flow rate. If the flow then comes in spurts or in any other nonuniform fashion (unsteady flow), some queuing results. In the design and expected performance evaluation of the Navigation/Traffic Control Satellite, the following factors pertaining to communications loading are of interest:

a) Probability of saturation

b) Utilization rate

c) Expected number of messages in the system

d) Expected message time

e) Probability of excessive message time

These factors can be evaluated by applying the results outlined by Kleinrock (Reference 1) where he successfully applied queuing theory to the analysis of multichannel communication networks. Since the communication between aircraft, marine vehicles and various ground stations involves stochastic message flow, queuing theory is well suited to this purpose. To describe the queuing process properly, the following factors must be specified. (For a reasonably complete list, see Reference 2.)

a) The message arrival statistics (i.e., the distribution of the arrival times of the messages).

b) The service statistics (i.e., the distribution of the time it takes the satellite to transmit each message).

c) The rules for forming and maintaining the queue (i.e., the maximum number of messages the storage facility can hold and the queue discipline).

d) The number of channels available for message transfer.

In the communications load analysis described herein, the following assumptions are made concerning these factors:

a) Messages arrive at the satellite according to a Poisson distribution with an average arrival rate of λ messages per minute. Since the Poisson distribution corresponds to random arrivals of messages at the satellite for a small time interval, this assumption appears to be quite reasonable for this situation.

b) Although the distribution of the length of aircraft and marine messages has not been investigated in this analysis, studies of telephone messages show that the length of these messages follows an exponential distribution. Thus, it is assumed that the length of aircraft and marine messages will also follow an exponential distribution with an average length of $1/\mu_D$ bits per message in the case of digital messages and $1/\mu_V$ words per message for voice transmissions.

c) The queue discipline assumed in this model is a first-come-first-served discipline. When a communication is originated, the originator will attempt to find an open channel. If all the channels are busy, the originator will enter a single queue and subsequentially be serviced on a first-come-first-served basis as soon as a channel becomes available. It can be shown that the results obtained when such a discipline is employed are practically equivalent to the case where a random service discipline is assumed (Reference 13).

d) The system has N_D digital channels each with a transmission rate of C_D bits per second and N_V voice channels each with a transmission rate of C_V words per second.

Based upon these assumptions, a number of relationships, developed in Reference 1 by Kleinrock are as follows:

Probability of Saturation

$$P(\geq N) = \frac{P_O (N\rho)^N}{(1-\rho)N!} \tag{15}$$

where

$$P_O = \left[\sum_{n=O}^{N-1} \frac{(N\rho)^n}{n!} + \frac{(N\rho)^N}{(1-\rho)N!} \right]^{-1}$$

$P(\geq N)$ = Probability that the number of messages in the system is greater than or equal to N, the number of channels.

Utilization Rate

$$\rho = \frac{\lambda}{u NC} \tag{16}$$

ρ = Expected system utilization or the fraction of the time that the system is busy.

Expected Number of Messages in the System

$$E(n) = \frac{\rho}{1-\rho} N(1-\rho) + P(\geq N) \tag{17}$$

$E(n)$ = The expected value of the number of messages in the system.

Expected Message Time

$$T = \frac{1}{\mu C} + \frac{P(\geq N)}{(1-\rho)\mu NC} \tag{18}$$

T = The expected value of the total time that a message spends in the system.

Probability of Excessive Message Time

$$P(>t) = \frac{N(1-\rho) - P(<N)}{N(1-\mu)-1} e^{-\mu Ct} - \frac{P(\geq N)}{N(1-\rho)-1} e^{-(1-\rho)\mu NCt} \tag{19}$$

$P(>t)$ = Probability that the total time that a message spends in the system is greater than t.

where

$$P(<N) = 1 - P(\geq N)$$

$P(<N)$ = Probability of immediate access to the system.

In these equations subscripts have been removed from the parameters C and N since these equations apply to both digital and voice communications. Solution of Equations 15 through 19 depends upon specification of the following input data:

a) The average arrival rate, λ, of both digital and voice messages at the satellite or satellites.

b) The average length of a message in bits/message, $1/\mu_D$, and words/message, $1/\mu_V$.

c) The transmission rate of each channel in bits per second, C_D, for digital messages; and words per second, C_V, for voice messages.

d) The number of digital channels, N_D, and voice channels, N_V, in the satellite or satellites.

A value for C_V, voice transmission rate, is determined by channel clarity, message content, and human factors such as variations in verbalizing from normal conversation rate. C_V would normally vary from one to three words per second. Digital transmission rate, C_D, the number of digital channels, N_D, and the number of voice channels, N_V, are design parameters whose design values must be determined from the analysis. Values for arrival rate, λ, and message length, $1/\mu$, can be estimated with reasonable accuracy by utilizing existing traffic forecasts and by performing an analysis of typical aircraft and marine messages. The sections which follow describe these analyses.

3.3 AIRCRAFT MESSAGE ANALYSIS

To determine the total aircraft communications traffic loads, the operational communications requirements first have to be described. The principal classes of communications (other than emergency) are Advisory, Traffic Control, and Company Business. These are broken down into the following types of messages (these categories are similar to those used in References 3 through 6):

0 Call Up, Response, Address, Signature, Acknowledgment, and Sign Off

1 Position Report

2 Position Determination

3 In Flight Weather

4 Terminal Forecast

5 ARTC Traffic

6 Company Communications

7 Radio/IFF Checks

8 Repeats

Note: Emergency communications on separate channels.

It is somewhat difficult to project a message analysis from today's intercontinental air traffic situation, wherein aircraft transmit their messages over relatively unsatisfactory, high-frequency voice links, and are given only a loose flight following service, to a situation where mixed subsonic and supersonic transports are given high quality air traffic control service with much tighter tolerances on track-keeping, and very high quality voice and data communications links with which to work. However, experience has been gained in air traffic control situations similar to that which will prevail over the North Atlantic in 1975, namely, the high altitude positive controlled airways over the continental U.S. today. This similarity, it is felt, will allow an adequate estimate of the nature of the communications load over the North Atlantic in 1975. Thus, in the following sections a total communications load is postulated based on messages of the foregoing types. It was assumed that separate channels will be provided for emergency communications.

3.3.1 Length of Typical Messages

A selection of typical messages can be found in Figure 10. These messages were constructed from talks with people acquainted with aircraft communications and from information gathered from References 16 and 3 through 7. The type zero message is sent every time message types 1 through 8 are sent. Types 1 through 8 represent the information that the originator wishes to convey while the zero type message contains the additional information that must accompany each message in order to effect proper communications. In the operational situation, a particular communication channel will be utilized during the time the content portion of the message (types 1 through 8) is being sent as well as during the call up, response, address, signature, and sign-off portion of the total message (type 0). Thus, the true message length is the sum of the number of words in the type 1 through 8 message and the number of words in the type zero message. Hence, 45 words must be added to message types 1 through 8 of Figure 10 in order to estimate the total length of each of these messages.

Message	Voice: Typical Message	Voice: Word Length	Digital: Abbrev. Mess.*	Digital: Bit Length
(0) Call Up, Response, Address, Signature, Sign-Off A-G G-A	a. New York Oceanic Control this is Trans World six two eight over b. Trans World six two eight this is New York Oceanic Control over c. New York Oceanic Control d. Trans World six two eight, over e. Roger six two eight on your position report New York out	45	a. NYOC this is TW628 K b. TW628 this is NYOC K c. NYOC d. TW628 K e. R 628 on PR NYO	536
(1) Position Report A-G	Trans World six two eight, one three three zero zulu latitude four two decimal five degrees, longitude six two decimal five degrees, flight level three zero zero** Estimate Shannon one four zero zero zulu, fuel remaining six zero zero zero, outside air temperature five two degrees centigrade, wind nine five degrees, dog factor plus two five zero feet, in clouds, icing light, turbulence light. ** Short report stops here	27 short 64 long	TW 628, 1330Z, Lat 42.5, Lon 62.5, FL 300** ETA Shan 1400Z, FR6000, OTA 52, Wind 95D, DF +250 In C, Ice, Fbl, Turb Fol.	776
(2) Position Determ. G-A	New York Oceanic Control has a Nav Sat fix on you. Your position latitude four two decimal five degrees, longitude six two decimal five degrees at thirteen hundred zulu.	29	NYOC has N/S fix on U. Your Psn Lat 42.5, Lon 62.5 1300Z	416
(3) In Flight Weather A-G	Pan Am three six seven encountered moderate turbulence at flight level three zero zero between four two and four three degrees latitude and six two decimal five degrees longitude	32	PA 367 Enco Mod Turb at FL 300 Betw 42 and 43 Lat and 62 and 62.5 Lon	512
(4) Terminal Forecast G-A	JFK reporting one six one five zulu ceiling two thousand feet visibility one mile wind nine five degrees one zero knots, temperature five five, dew point four seven. Rain shower ended one six zero zero.	36	JFK Rpt 1615Z Ceil 2,000 Vis 1, Wind 95 D 10 Knt, T 55, DP 47. Ra Show End 1600Z	544
(5) ARTC Traffic				
A-G	Trans World six two seven estimate Shannon at two four, request flight level three zero zero	16	TW627 ETA Shan at 24, Req FL 300	240
G-A	Trans World six two seven descend and maintain flight level three zero zero report reaching	15	TW627 Des and Mntn FL 300 RR	216
(6) Company Comm.				
G-A	Trans World six two seven message for VIP Laurence J. Smith to call Washington office on landing important. Also request number of passengers by class	27	TW627 Mes for VIP L. J. Smith to Call Wash Off on Land Imp. Also Req No of Pass by Class	664
G-A	Roger on VIP Smith message. Passenger loading two one first class and seven nine coach.	17	R on VIP Smith Mess. Pass Lod 21 Frst Cls and 79 Coach	424
(7) Radio/IFF Checks				
A-G	Trans World seven two seven monitoring one three five decimal six squawking mode three code two two.	17	TW727 Montr 135.6 Squaw Mode 3 Code 22	280
G-A	Shannon control requests you reply mode two code zero one and identify	12	Shan Con Req U ID Mode 2 Code 01 and Ident	320
(8) Repeats A-G G-A	Roger climb and maintain flight level four zero zero report when reaching	12	R Clb and Mntn FL 400 RR	184

*A form of teletype mechanization, which is not necessarily optimum

Figure 10. Message Length Estimation

For the digital communication case, it was necessary to digitize the voice messages and then to determine the corresponding number of bits required to represent them. The method of digitizing employed was first to abbreviate each message to obtain a reasonable estimate of the number of characters in each digital message. Once this was accomplished, the number of bits corresponding to each message was obtained by multiplying the number of bits per character times the total number of characters. This relatively crude method of abbreviating and digitizing, essentially teletyping, is certainly somewhat less efficient than "canning" or "coding" and is therefore somewhat conservative. Present digital communications systems normally employ codes ranging from 5 to 8 bits per character. The 8 bit code is a standard digital code and has the advantage over the standard 5 bit teletypewriter code of employing an error-detection feature; hence, this code will probably be used in communication systems for the 1975 time period. For this reason the bit lengths for the messages shown in Figure 10 have been calculated for this 8 bit per character code.

To give a valid representation of digital message length, it is necessary to incorporate the amount of time required for the user to acquire the center frequency of the transmitted message signal (acquisition time) and the time required for the user's receiving equipment to be synchronized with the transmitted message (synchronization time) into the estimate of average message length. Although acquisition time varies with the digital system being considered, 50 milliseconds represents a reasonable estimate for this time. Since acquisition time effectively lengthens each message, this effect can be considered by taking the product of this 50 millisecond time and the transmission rate and adding the resultant number of equivalent bits to the message length. For a transmission rate of 500 bits/second, for example, this would result in the addition of 25 equivalent bits to the average message length. It was also determined that synchronization time can be included by an addition of 10 percent of the original average message length or by 10 bits, whichever is greater. By making these appropriate additions of the effects of acquisition time and synchronization time on message length, the effective digital message length can be obtained.

3.3.2 Estimate of Number of Contacts Between Aircraft and Ground Station

Each type of message (i.e., types 1 through 8) has its own particular contact rate which depends primarily on the message origin (aircraft or ground station, type of aircraft involved) supersonic or subsonic, weather, and other contingencies. To establish a reasonable estimate of the contact rate for each type of message, References 6 and 11 were utilized as well as talks with people closely acquainted with aircraft communications. From these sources estimates of the number of contacts per trip were established for each type of aircraft, as shown in Figure 11. A typical flight across the North Atlantic is on the order of 4000 miles, and it is assumed that the aircraft would be controlled for the first and last 200 miles of the trip by local approach and departure control agencies. Thus, the aircraft would typically be using the service of the Navigation/Traffic Control Satellite for en route traffic control for approximately 3600 miles of the trip.[1] Since the cruise speed of a subsonic aircraft is approximately 600 miles per hour and that of a supersonic aircraft is approximately 1800 miles per hour, the length of the time each type of aircraft would be under control of the Navigation/Traffic Control Satellite is approximately 6 and 2 hours, respectively. From this information the total contact rate in messages per unit time and, hence, the average arrival rate of messages at the satellite can readily be established (see Figure 11).

3.3.3 Summary of Aircraft Message Analysis - Voice Portion

Thus far estimates for the maximum number of aircraft in the North Atlantic corridor and estimates concerning the word length of typical messages as well as the contact rate of these type messages have been obtained. The next step in the analysis is to compute the average length

---

[1] Actually, direct air-ground-air transmissions are possible between New York and Newfoundland for the Northernmost tracks, but might not be possible for Southern tracks. It is assumed here that the NTL Satellite is used when the aircraft is not within line-of-sight of New York or London.

Message Type		Air-to-Ground	Ground-to-Air
1a	Position Report (Long)	4 per trip	N/A
1b	Position Report (Short)	8 per trip	N/A
2	Position Determination	N/A	2 per trip
3	In Flight Weather	1 per trip	N/A
4	Terminal Weather	N/A	1 per trip
5	ARTC	5 per trip	5 per trip
6	Company Communications	3 per trip	3 per trip
7	Radio/IFF Check	3 per trip	3 per trip
8	Repeats	2 per trip	2 per trip
	Totals	26 per trip	16 per trip

Figure 11. Estimation of the Number of Contacts per Trip for Aircraft

of a random message and the average arrival rate of messages at the satellite. To find the average length of a random message, the following notation is employed:

$1/\mu_{Vi}$ = Number of words per type i voice message

λ_{Vi} = Arrival rate of type i voice messages (messages per hour)

$AWPVM_1$ = Average words per voice message of the supersonic air to ground type

$AWPVM_2$ = Average words per voice message of the supersonic ground to air type

$AWPVM_3$ = Average words per voice message of the subsonic air to ground type

$AWPVM_4$ = Average words per voice message of the subsonic ground to air type

TAWPVM = Total average words per voice message of supersonic and subsonic air to ground and ground to air types

The calculations were made using the fact that

$$AWPVM_j = \frac{\Sigma 1/\mu_{Vi} \cdot \lambda_{Vi}}{\Sigma \lambda_{Vi}}$$

where j = 1, . . . , 4 corresponding to the four general message categories and i = 1, . . . , 8 corresponding to the eight types of messages. The results are summarized in Figures 12 through 15 and indicate the average message length of the four general message types. To find the total average words per message, each of these intermediate results must be weighted by the total number of aircraft of each type (i. e., 170 subsonic and 20 supersonic aircraft). Thus, the expression for the Total Average Words Per Voice Message (TAWPVM) is as follows:

$$TAWPVM = \frac{(AWPVM_1)(20) + (AWPVM_2)(20) + (AWPVM_4)(170)}{380}$$

TAWPVM = 68 words per message

$(T\lambda)_{V1}$ = Total arrival rate of voice messages (messages per hour) of the supersonic air to ground type

$(T\lambda)_{V2}$ = Total arrival rate of voice messages (messages per hour) of the supersonic ground to air type

$(T\lambda)_{V3}$ = Total arrival rate of voice messages (messages per hour) of the subsonic air to ground type

$(T\lambda)_{V4}$ = Total arrival rate of voice messages (messages per hour) of the subsonic ground to air type

TNVMPH = Total number of voice messages per hour of the subsonic and supersonic air to ground and ground to air types

Message Type	Words Per Message $1/\mu_{Vi}$	Messages Per Hour λ_{Vi}	$(1/\mu_{Vi}) \cdot (\lambda_{Vi})$
1a Position Report (Long)	109	2	218.
1b Position Report (Short)	72	4	288.
3 In Flight Weather	77	0.5	38.5
5 ARTC Traffic	61	2.5	152.5
6 Company Comm.	62	1.5	93.
7 Radio/IFF Check	62	1.5	93.
8 Repeats	57	1	57.
Totals		13.	940.

$$\text{Average Words Per Message } (AWPVM_1) = \frac{\Sigma(1/\mu_{Vi})(\lambda_{Vi})}{\Sigma\lambda_{Vi}} = \frac{940}{13} = 72$$

Figure 12. Average Length of Air to Ground Voice Messages for Supersonic Aircraft

To determine the total number of messages per hour, the total arrival rate for each type of communication (i.e., air-to-ground or ground-to-air) had to be weighted by the corresponding number of aircraft (i.e., 170 subsonic and 20 supersonic). (See Figures 12 through 15.) Consequently, the expression for the Total Number of Voice Messages Per Hour (TNVMPH) is:

$$TNVMPH = (T\gamma)_{V_1}(20) + (T\gamma)_{V_2}(20) + (T\gamma)_{V_3}(170) + (T\gamma)_{V_4}(170)$$

Message Type	Words Per Message $1/\mu_{Vi}$	Messages Per Hour λ_{Vi}	$(1/\mu_{Vi}) \cdot (\lambda_{Vi})$
2 Position Determ.	74	1	74
4 Terminal Forecast	81	0.5	40.5
5 ARTC Traffic	60	2.5	150
6 Company Comm.	72	1.5	108
7 Radio/IFF Check	57	1.5	85.5
8 Repeats	57	1	57
Totals		8	515

$$\text{Average Words Per Message } (AWPVM_2) = \frac{\Sigma(1/\mu_{Vi})(\lambda_{Vi})}{\Sigma\lambda_{Vi}} = \frac{515}{8} = 64$$

Figure 13. Average Length of Ground to Air Voice Messages for Supersonic Aircraft

TNVMPH = 1603.2 messages per hour = 0.44 messages per second

From this the total arrival rate of messages at the satellite in messages per second is $\frac{1603.2}{3600} = 0.44$. The estimates of the total average words per message of 68, and total arrival rate of messages of 0.44 messages per second are needed for the remaining analyses that are to be performed, for they represent the base line estimates of $1/\mu_V$ and λV defined in Equations 15 through 19.

Message Type	Words Per Message $1/\mu_{Vi}$	Messages Per Hour λ_{Vi}	$(1/\mu_{Vi}) \cdot (\lambda_{Vi})$
1a Position Report (Long)	109	0.66	71.9
1b Position Report (Short)	72	1.33	95.7
3 In Flight Weather	77	0.16	12.3
5 ARTC Traffic	61	0.83	50.6
6 Company Comm.	62	0.50	31
7 Radio/IFF Check	62	0.50	31
8 Repeats	57	0.33	18.8
Totals		4.31	311.3

$$\text{Average Words Per Message } (AWPVM_3) = \frac{\Sigma(1/\mu_{Vi})(\lambda_{Vi})}{\Sigma\lambda_{Vi}} = \frac{311.3}{4.31} = 72$$

Figure 14. Average Length of Air to Ground Voice Messages for Subsonic Aircraft

3.3.4 Summary of Aircraft Message Analysis - Digital Portion

The average length of a random digital message is found by digitizing abbreviations of the voice messages by use of an 8 bit per character code as illustrated in Figure 10. Because of the acquisition and synchronization times, this estimate must be augmented as described in Section 3.3.1. The amount by which the average message length is increased depends upon the transmission rate under consideration; hence, this rate must be selected before the average length of a digital message can be calculated.

Message Type	Words Per Message $1/\mu_{Vi}$	Messages Per Hour λ_{Vi}	$(1/\mu_{Vi})$ (λ_{Vi})
2 Position Determ.	74	0.33	24.4
4 Terminal Forecast	81	0.16	12.9
5 ARTC Traffic	60	0.83	49.8
6 Company Comm.	72	0.50	36.
7 Radio/IFF Check	57	0.50	28.5
8 Repeats	57	0.33	18.8
Totals		2.65	170.4

$$\text{Average Words Per Message } (AWPVM_4) = \frac{\Sigma(1/\mu_{Vi})(\lambda_{Vi})}{\Sigma\lambda_{Vi}} = \frac{170.4}{2.65} = 64$$

Figure 15. Average Length of Ground to Air Voice Messages for Subsonic Aircraft

A reasonable lower bound on this transmission rate is approximately 75 bits/second, and this corresponds to the rate achieved by conventional teletype equipment. To evaluate the impact of transmission rates upon the communications channel requirements of the Navigation/Traffic Control Satellite, the ensuing analysis is performed for three transmission rates, 75, 500, and 1000 bits per second.

Employing the techniques described in Section 3.3.3 for determining the total average word per voice message (TAWPVM) of 68 words, in conjunction with adding the effects of acquisition time and synchronization time on message length discussed in Section 3.3.1, yields the total average bits per digital message (TABPDM) for the three transmission rates of interested listed below:

Transmission Rate (bits/second)	Average Message Length (bits)
75	992
500	1013
1000	1038

The digital message arrival rate is identical to the rate of 0.44 messages per second obtained for the voice message in Section 3.3.3 as only the format of the message has been changed, and this does not affect the arrival rate.

These estimates of the total average bits per digital message (TABPDM) and the total arrival rate of 0.44 messages per second represent the baseline estimates of the digital message bit length ($1/\mu_D$) and the digital message arrival rate per second (λ_D) defined in Equations 15 through 19. With the aid of these baseline values, Equations 15 through 19 can be solved and the digital transmission rate C_D and the number of channels N_D required for various values of system performance can be obtained. These analyses are described in Section 3.5.

3.4 PRELIMINARY AIRCRAFT ALL-VOICE COMMUNICATIONS REQUIREMENTS

3.4.1 Analysis

As indicated in Section 3.1, the only design parameter for an all voice system is N_V, the number of voice channels, since the transmission rate, C_V, is determined by the expected speech rate of the conversants. For this first series of calculations a voice transmission rate of $C_V = 1$ word per second was selected since it represents a conservative estimate[2] of this speech rate. Equation 15 plotted in

[2]Although a typical conversation rate might be as high as 3 words per second, a range of from one to three words per second was investigated in order to account for the effects of low signal-to-noise ratio, inefficient speech, unnecessary verbiage, waiting time, and cut-outs.

Figure 16 describes the probability that the number of messages at the satellite exceeds the number of channels and, as expected, the probability of this event decreases as the number of channels is increased. Examination of Figure 16 shows that a variety of performance criteria can be selected for the situation described. For the Navigation/Traffic Control satellite a value of 0.05 for the probability that the number of messages exceeds the number of channels is felt to be adequate. Applying this performance criteria to the baseline case of an average message length of 68 words yields a channel requirement of 40 channels. This, in effect, means that if 40 channels are provided for an all voice system there is a 95 percent probability that an aircraft or ground station desiring an open channel will obtain one and a 5 percent probability that all channels will be occupied.

Although the feasibility of providing 40 voice channels depends upon 1975 technology, the particular frequency band used, the number of satellites provided, as well as other factors, it appears that 40 channels is a somewhat larger number of channels to provide than is desirable. In Figure 16, curves for average message length of from 50 to 80 words are also presented to show the impact of average message length upon the number of voice channels required for various system performance criteria.

It is interesting to compare this case of stochastic flow with the steady flow situation. Suppose that messages arrived at the satellite at a constant rate of 0.44 messages per second (i.e., 1 message every 2.29 seconds) and suppose further that each message is exactly 68 words in length. In this case, for a voice transmission rate of one word per second, approximately $68/2.29 \approx 30$ channels would be required in order that no queue would arise. This example illustrates that stochastic message flow requires over 33 percent more channels than does the steady flow case for the same performance.

Thus far one performance criteria or measure of effectiveness has been described. Figure 17, which depicts the solution of Equation 18, describes another measure of system performance; that is, the impact of the number of channels on the expected time a message spends in the system. By definition this time equals queuing time plus

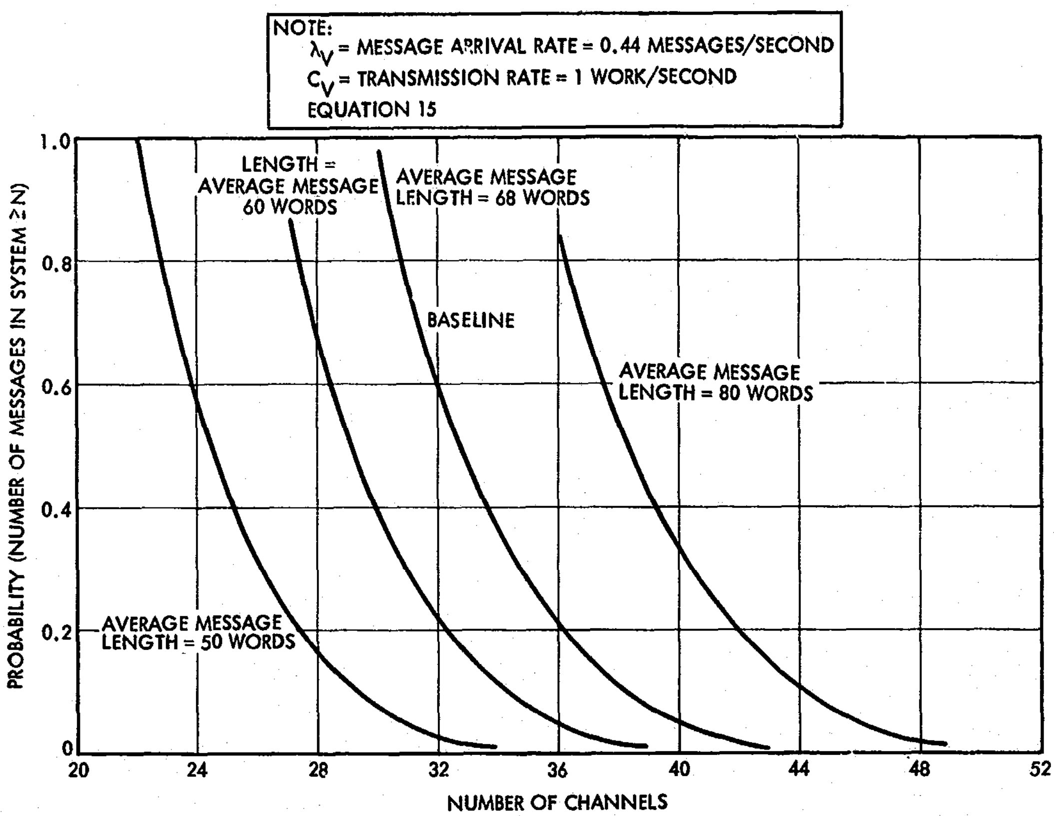


Figure 16. Probability that the Number of Voice Messages in the System is ≥N Channels

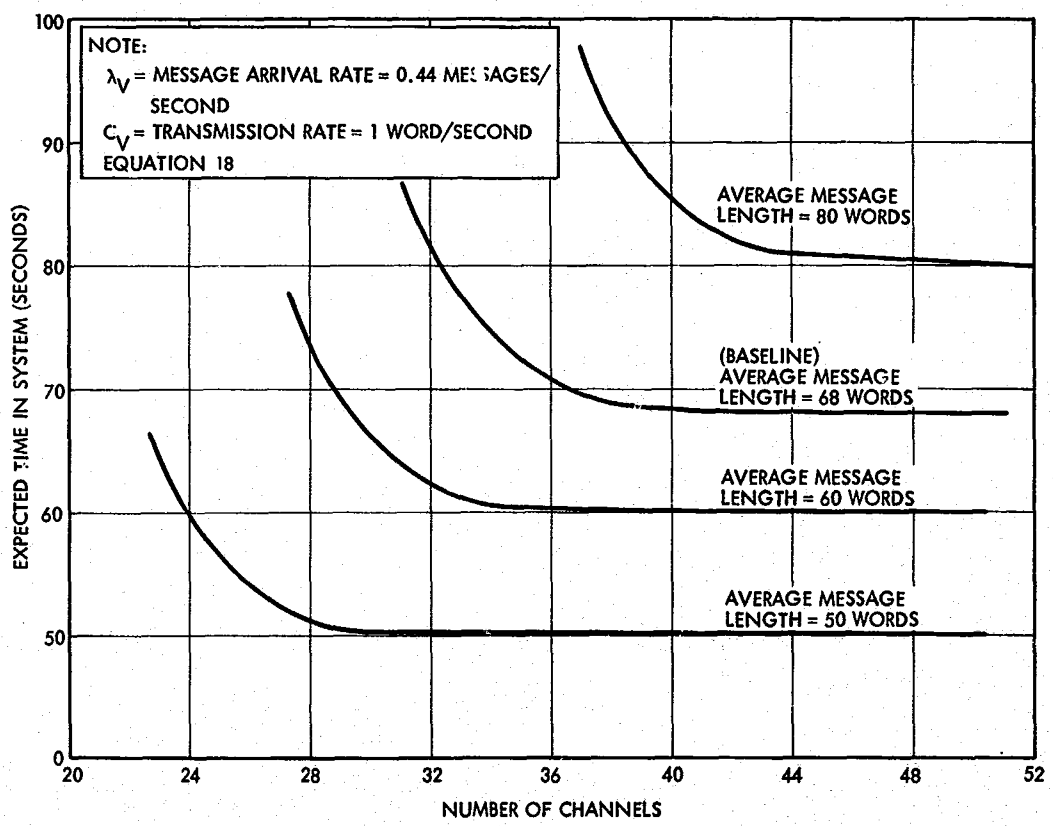


Figure 17. Expected Time a Voice Message Spends in the System

service time. The flat part of the curves of Figure 17 represents the situation where there is negligible queueing of messages; thus, the time a message spends in the system for this part of the curve corresponds to service time. For the baseline case of average message length = 68 words and a transmission rate of one word per second if 40 channels are provided, the expected time a message spends in the system is approximately 68 seconds (see Figure 17). If fewer than 40 channels are provided in the baseline case, the expected time a message spends in the system starts increasing rapidly. Thus, approximately 40 channels are required to minimize this particular measure of system performance.

Figure 18 describes the expected number of message in the system (Equation 22) and is similar to Figure 17 in that the flat portion of the curve again represents the situation where queueing is negligible. For the baseline case of an average message length of 68 words, 40 channels correspond to the point which yields the number of channels required to minimize the expected number of messages in the system. Figure 18, like Figure 16 and 17, also illustrates that the number of channels required for optimum system performance is quite sensitive to the average message length.

Figure 19 describes Equation 23, which is system utilization or the percentage of the time that the system is busy. For the baseline case of an average message length of 68 words and 40 voice channels, the system utilization as seen from Figure 19 is approximately 75 percent. This means that each channel of the system will be idle approximately 25 percent of the time. This result conforms well with results obtained from an analysis of similar systems which handle stochastic flow in which the messages do not arrive at a predictable rate. Thus, there are times when the system is processing very few messages and other times when all the channels are occupied due to the nonuniform manner in which messages arrive and are serviced by the satellite. Since this is an analysis of peak traffic conditions, the utilization will probably be much lower during slack hours.

Equation 24, which describes the probability that the message is in the system for a time greater than t seconds, is plotted in Figure 20 for the baseline case of 68 words. Figure 20 shows that increasing the number of channels from 31 to 35 results in a rather substantial decrease in this probability. Increasing the number of channels from 35 to 40

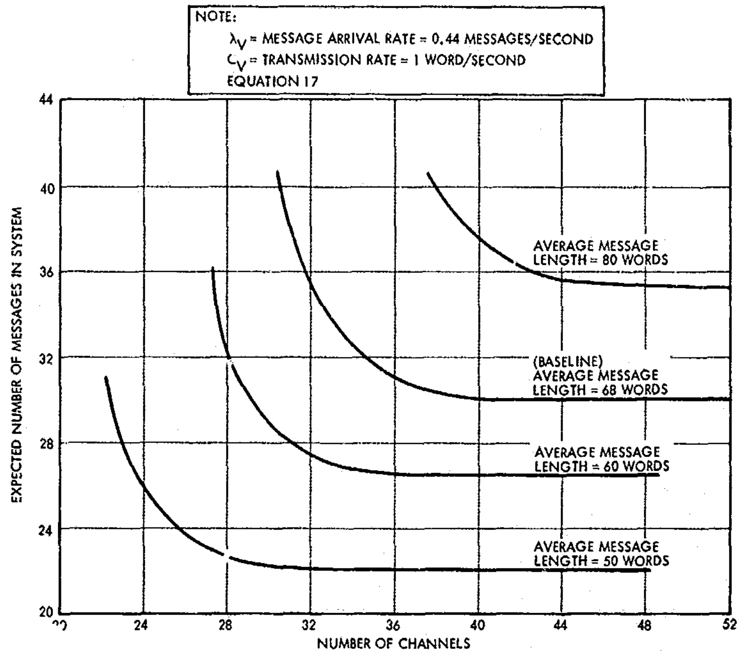


Figure 18. Expected Number of Voice Messages in the System

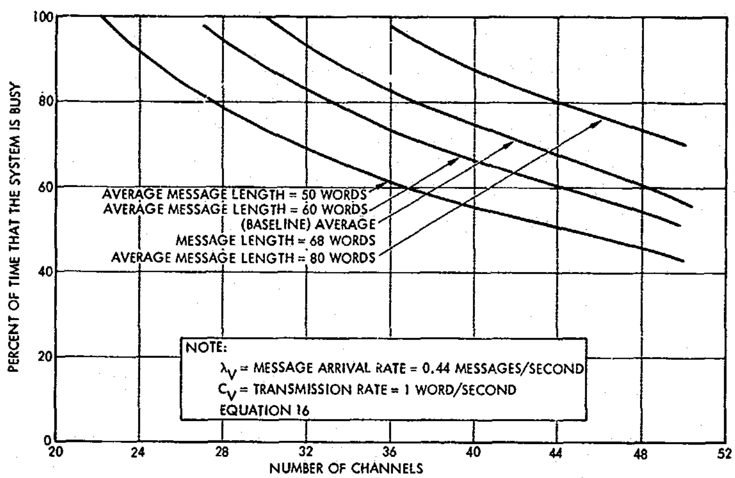


Figure 19. Voice Messages

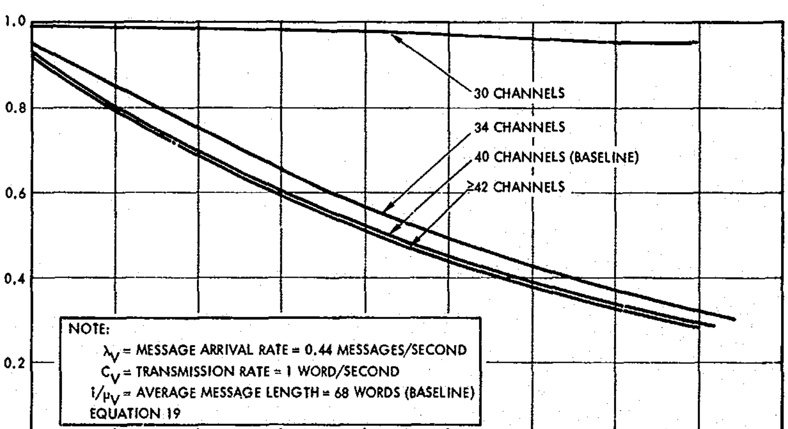


Figure 20. Probability Voice Message in the System for Time > t Seconds

results in a moderate decrease in this probability while increasing the number of channels beyond 40 has little effect on the probability.

3.4.2 Summary

3.4.2.1 Low Voice Rate

The results of the analysis for an all-voice system with a transmission rate of one word per second, an average arrival rate of messages at the satellite of 0.44 messages per second, and an average message length of 68 words per message indicates that approximately 40 voice channels correspond to the following system performance:

a) A probability of 0.95 that at least one channel will be open at any time during peak traffic.

b) The least number of channels required to minimize the expected time a message spends in the system.

c) The least number of channels required to minimize the expected number of messages in the system.

d) The heuristic optimum[3] number of channels required to minimize the probability that a message is in the system for a time greater than some given time t.

Furthermore, this analysis has shown that the expected system utilization for 40 channels for the baseline case is approximately 75 percent.

3.4.2.2 High Voice Rate

The results of the analysis for a transmission rate of three words per second is presented below. Since these results are obtained in the same manner as previously described for the case of a transmission rate of one word per second, the figures corresponding to Figures 16 through 20 have not been depicted. For an all-voice system with a transmission rate of three words per second, an average arrival rate of messages at the satellite of 0.44 messages per second, and an average message length of 68 words per message, 16 channels correspond to the following system performance:

a) A probability of 0.94 that at least one channel will be open at any time during peak traffic.

b) The least number of channels required to minimize the expected time a message spends in the system.

c) The least number of channels required to minimize the expected number of messages in the system.

[3] Heuristic optimum implies that an optimum was not derived in a formal manner but instead was obtained by applying judgment to the graphical results.

d) The optimum number (i.e., heuristic optimum) number of channels required to minimize the probability that a message is in the system for a time greater than some given time t.

This analysis also shows that the expected system utilization for 16 channels for the baseline case in 63 percent.

Comparing these analyses it is seen that the transmission rate has a substantial influence upon the number of channels required for optimum system performance. Increasing the transmission by a factor of three for the baseline case decreases the required number of channels by a factor of 2.5. Unlike the case of steady flow, the transmission rate does not have a linear effect upon the required number of channels for the case of stochastic message flow.

3.4.3 Sensitivity Analysis

The channel requirements for an all-voice system are based upon the values of aircraft population corresponding to peak North Atlantic traffic, average message arrival rate at the satellite and average message length. Figures 21 through 23 describe the sensitivity of the results to changes in these quantities.

The traffic forecasts examined (see Section 2) indicate a peak number of aircraft in the North Atlantic which varies from 120 to 250 aircraft; thus, the required number of channels for this range of aircraft was examined and the results are presented in Figure 21. Since the references examined all agreed that the number of supersonic aircraft in the corridor at peak would be 20, the analysis is based upon a constant number of supersonic aircraft. As shown in Figure 21, the result is less sensitive for the high transmission rate of three words per second than it is for the relatively low rate of one word per second. From Figure 21, if the baseline estimate of the aircraft population is 10 percent higher than the baseline forecast, for example, the required number of channels increases from 16 to 17 channels for a transmission rate of three words per second and from 40 to 43 channels for a transmission rate of one word per second.

Figure 22 describes the sensitivity of average message arrival rate upon the required number of channels for optimum system performance and, as in Figure 21, the result is less sensitive for the higher

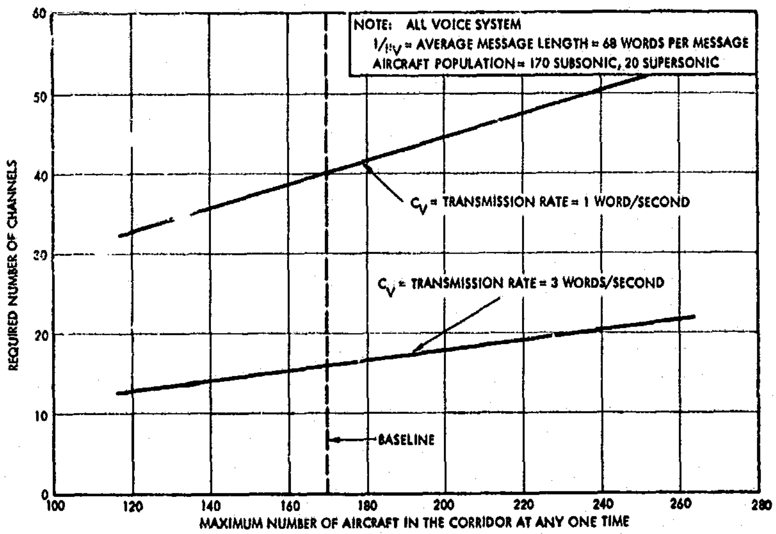


Figure 21. Impact of Aircraft Population Upon Required Number of Channels for 1975

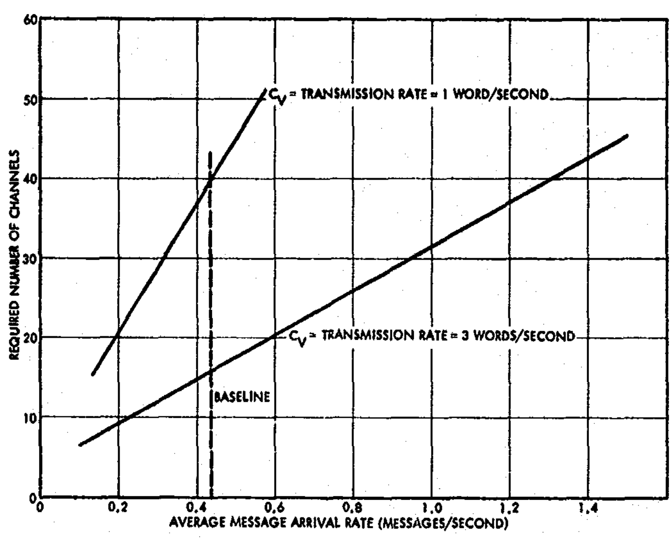


Figure 22. Impact of Average Message Arrival Rate Upon Required Number of Channels for 1975

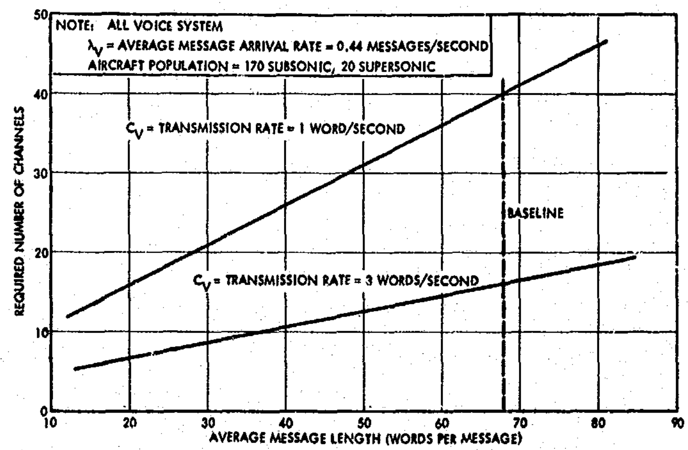


Figure 23. Impact of Average Length Upon Required Number of Channels for 1975

transmission rate of three words per second than it is for the lower bound of one word per second. From Figure 22, if the actual message arrival rate is 10 percent higher than the baseline estimate, for example, the required number of channels again increases from 16 to 17 for a transmission rate of three words and from 40 to 43 channels for a transmission rate of one word per second.

Figure 23 describes the sensitivity of average message length upon the required number of channels for optimum system performance. In this case a 10 percent increase in average message length yields the same result obtained from Figures 21 and 22.

3.5 PRELIMINARY AIRCRAFT ALL-DIGITAL COMMUNICATIONS REQUIREMENTS

With the values for average message arrival rate and average message length determined in Section 3.3.4, Equations 15 through 19 can be solved by use of the computer program described in Paragraph 3.11 and the transmission rate and the number of channels required for an optimum all-digital system can be determined in the same manner as described in Section 3.4. For the purpose of illustration, the utilization rate versus the number of channels available is presented in Figure 24 for each of the three transmission rates.

For a transmission rate of 75 bits per second with an augmented baseline average message length of 992 bits, the heuristic optimum number of channels required is 11 channels. For a rate of 500 bits per second with an augmented baseline average message length of 1013 bits, 4 channels give an heuristic optimum, and for a rate of 1000 bits per second with an augmented baseline average message length of 1038 bits, the heuristic optimum is 3 channels.

The results obtained are illustrated in Figure 25, which depicts the required number of channels as a function of the transmission rates. It is seen in this figure that for rates of less than 550 bits second, a significant reduction in channel requirements can be made by increasing the transmission rate. However, once the point where the channel requirement of 3 channels has been reached, which occurs for a transmission rate of approximately 550 bits per second, no further significant saving in channels required can be made by increasing the transmission

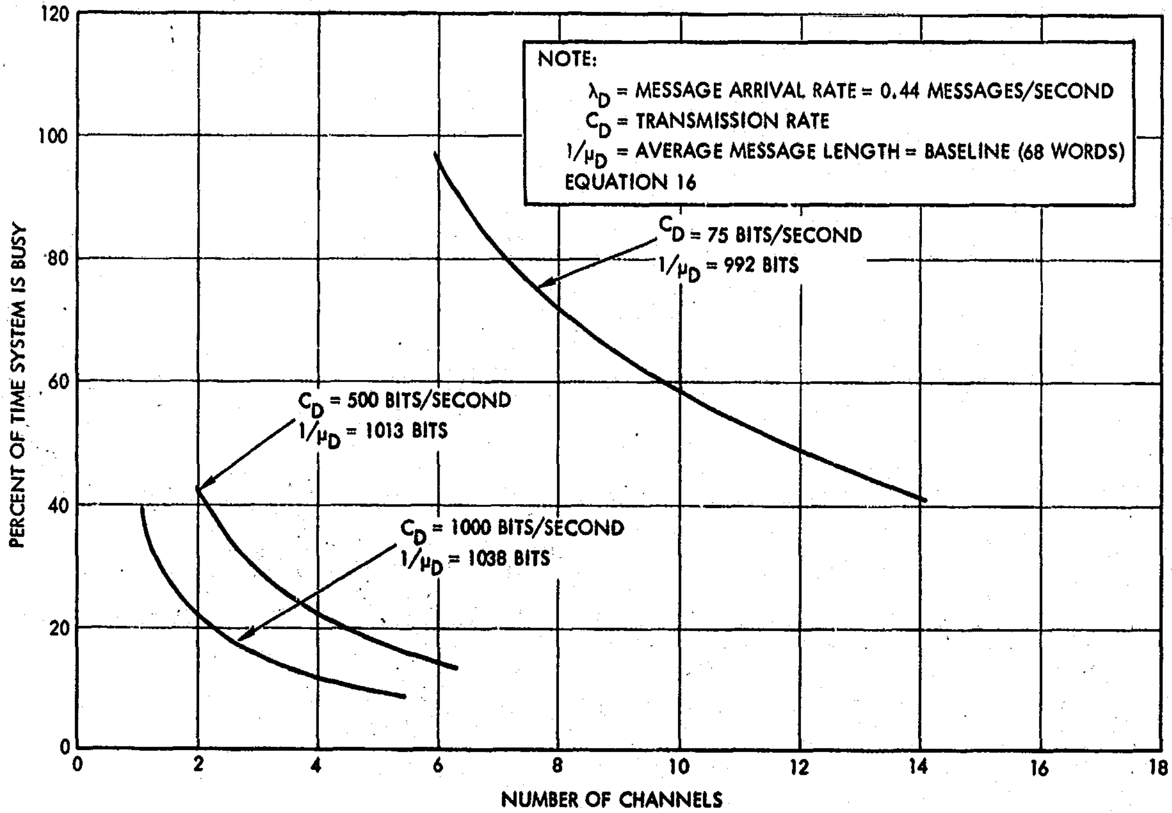


Figure 24. Percentage of Time that the System is Busy

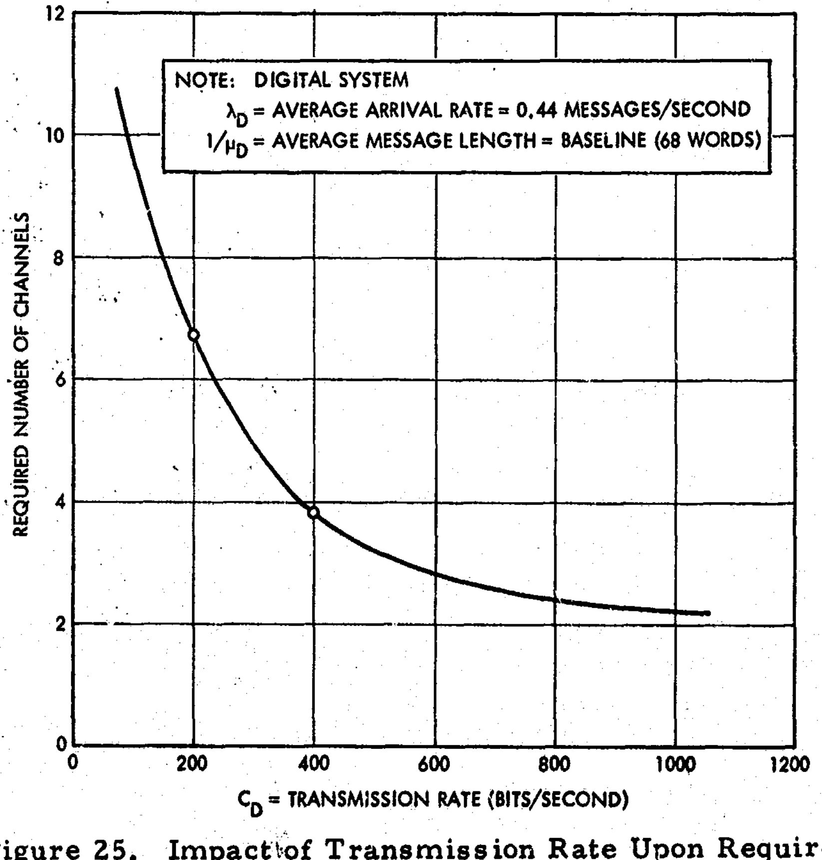


Figure 25. Impact of Transmission Rate Upon Required Number of Channels for 1975

rate. Although the final selection of optimum transmission rate depends upon the results of a hardware study, with respect to the operational viewpoint, the case of a transmission rate of 75 bits per second can be discarded. Transmission rates of less than 400 bits per second can also be discarded as a relatively small increase in transmission rate results in a significant reduction of channel requirements. For example, increasing the transmission rate from 100 to 300 bits per second results in a decrease from 10 channels to 5 channels required for optimum system performance. Therefore, the choice of the optimum transmission rate will depend on a communication equipment hardware effectiveness study concerning the utility of transmission rates of approximately 450 to 550 bits per second with 4 satellite digital communications channels versus the utility of transmission rates in the region of 700 to 800 bits per second with 3 channels, these central regions being chosen to allow for increased system utilization to occur without saturating the system. Since a hardware study is beyond the scope of this analysis, a transmission rate of 800 bits per second will be considered optimum for the purpose of this analysis since it requires the minimum number of channels.

At this point a comparison between the all-voice system and all-digital system can be made. The number of channels required for the digital case, 3 channels, is more than an order of magnitude less than the 40 channels required for an all-voice system. The feasibility of providing 3 digital channels is well within the available technology, while cursory analysis indicates that 40 voice channels might represent an undesirable requirement. Thus, with respect to channel requirements, the all-digital system appears to offer significant advantages over the all-voice system.

It is interesting to compare this case of stochastic flow with the steady flow situation for the all-digital system. For the baseline case, messages arrive at the satellite at the constant rate of one message every 2.29 seconds. For a transmission rate of 800 bits per second, the augmented baseline average message length is 1028 bits. If each message arriving at the satellite is exactly this length, it would require approximately 1.3 seconds to be processed. Thus, only one channel would be required to insure no queue would arise for the steady flow system as opposed to three channels required for the case of stochastic flow.

Thus far the digital transmission rate of 800 bits per second has been selected and the number of channels required for optimum system performance has been set at three channels. The next step in this analysis is to determine the performance of this baseline digital system. For this purpose Equations 15 through 19 were again solved and the results obtained were as follows:

For an all-digital system with a transmission rate of 800 bits per second, an average arrival rate of messages at the satellite of 0.44 messages per second, and an average augmented message length of 1028 bits per message, three channels correspond to the following system performance:

a) A probability of 0.98 that at least one channel will be open at any time during peak traffic.

b) The least number of channels required to minimize the expected time a message spends in the system.

c) The least number of channels required to minimize the expected number of messages in the system.

d) A total system utilization of 18 percent.

e) The heuristic optimum number of channels required to minimize the probability that a message is in the system for a time greater than some given time t.

3.5.1 Sensitivity Analysis

The channel requirements for an all-digital system are based upon the estimates of aircraft population corresponding to peak North Atlantic traffic, average message arrival rate, and average message length. Figures 26 through 28 describe the sensitivity of the results to changes in these quantities. Although the transmission rate of 800 bits

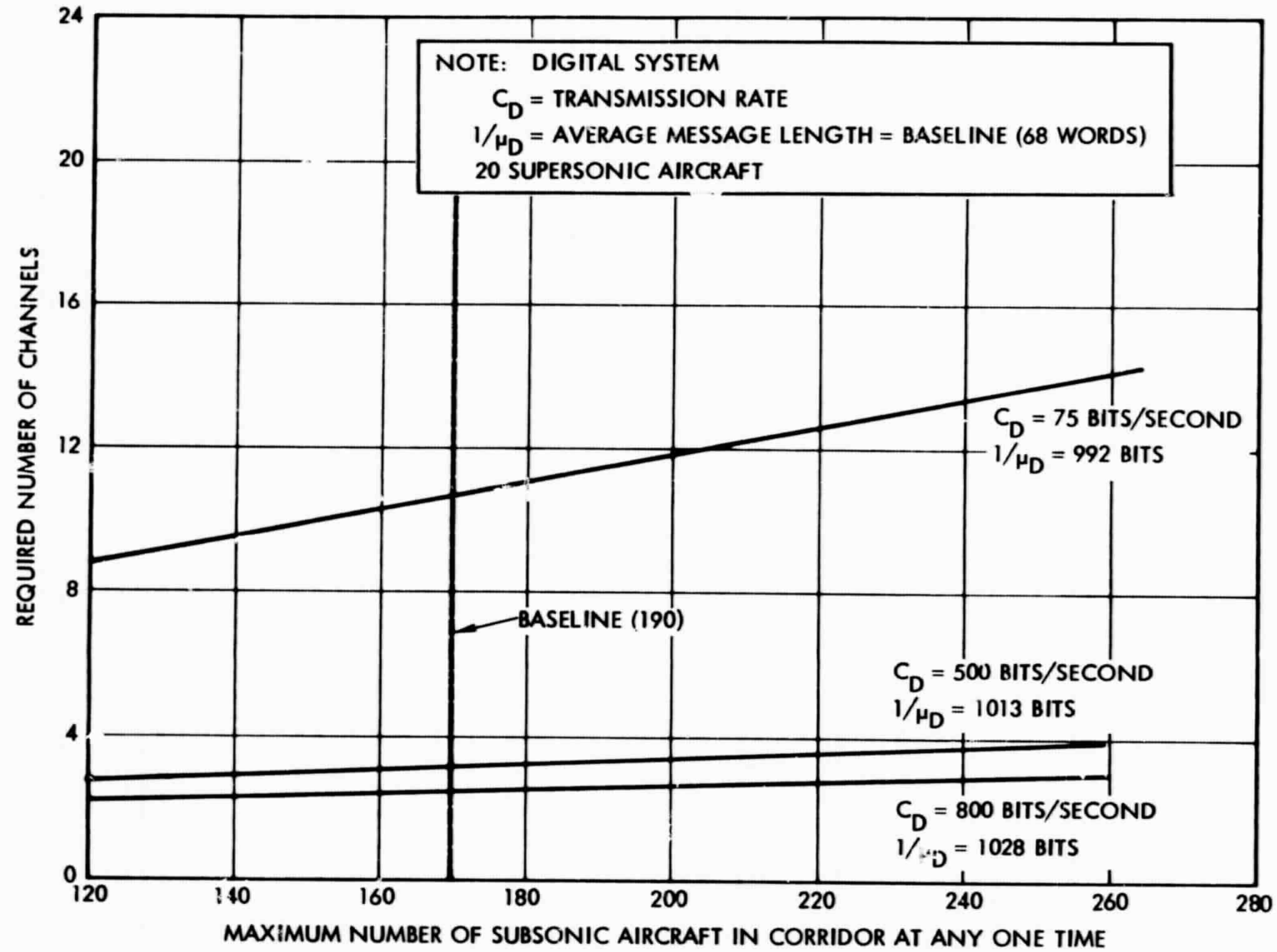


Figure 26. Impact of Aircraft Population on Required Number of Channels for 1975

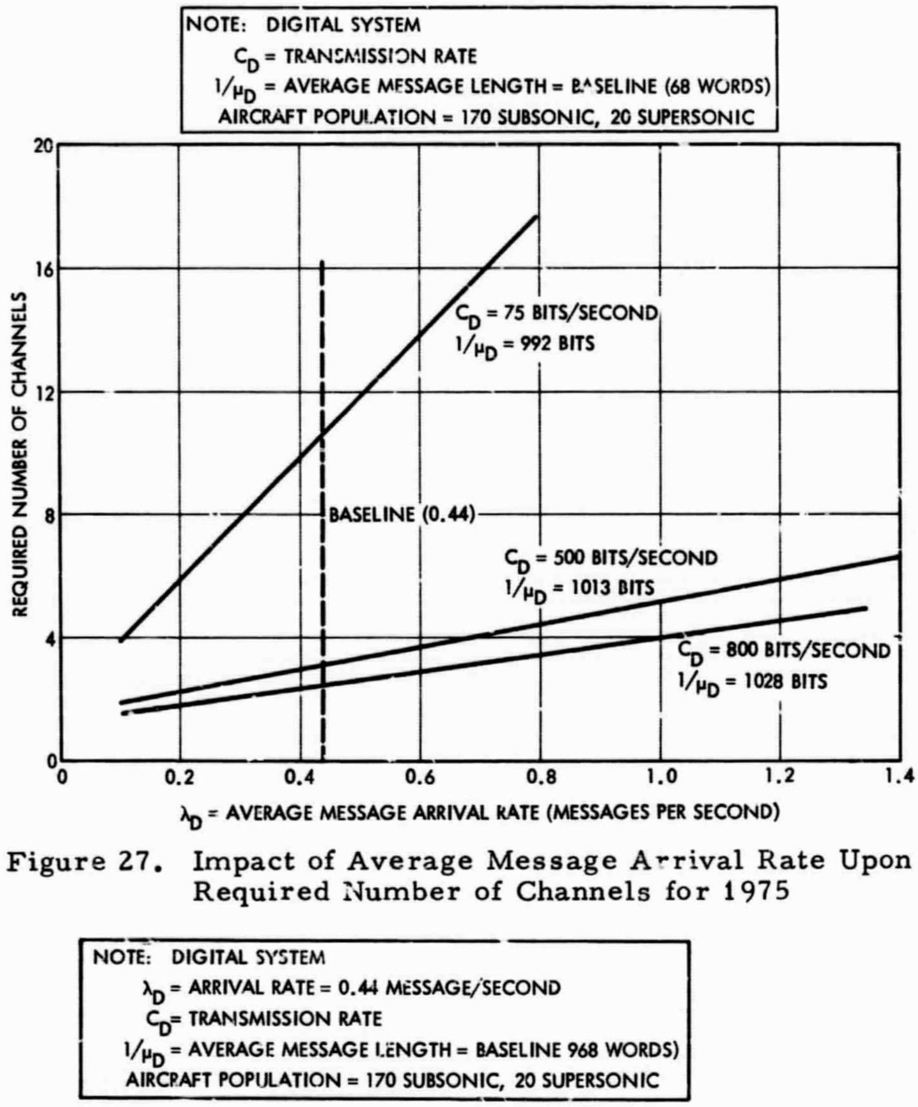


Figure 27. Impact of Average Message Arrival Rate Upon Required Number of Channels for 1975

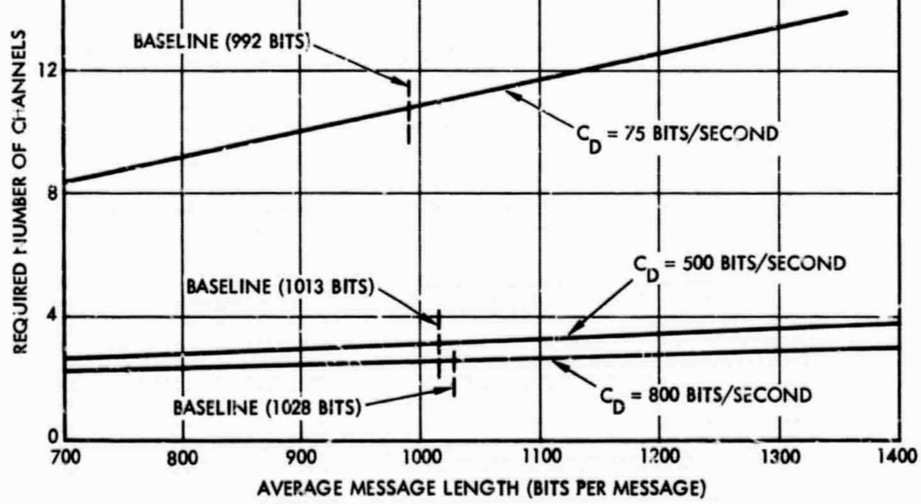


Figure 28. Impact of Average Message Length Upon Required Number of Channels for 1975

per second has already been selected as the optimum rate, transmission rates of 75 and 500 bits per second have been included in these figures so that the impact of various transmission rates upon required number of channels can also be evaluated.

Figure 26 shows the impact of the number of aircraft in the North Atlantic Corridor simultaneously upon channel requirements. In this figure the number of subsonic aircraft has been varied from 120 to 240 since these values correspond to the range of forecasts presented in Section 2. Figure 26 shows that the results are less sensitive to the accuracy of the baseline forecasts for high bit rates than for lower bit rates. The results obtained from this sensitivity analysis show that an increase in the baseline aircraft forecast of 50 percent yields no change in the required number of channels.

Figure 27 depicts the sensitivity of channel requirements to average message arrival rates for transmission rates of 75, 500, and 800 bits per second. For lower transmission rates such as 75 bits per second, channel requirements are much more sensitive than for higher rates such as 500 and 800 bits per second. If the arrival rate is 50 percent higher than the baseline estimate, the required number of channels for transmission rates of 500 and 800 bits per second remain at four and three channels, respectively.

Figure 28 describes the sensitivity of channel requirements to average message length for optimum system performance. As in the two previous cases, the sensitivity decreases with increasing transmission rates and the results are the same.

This sensitivity analysis indicates that at the transmission rate chosen the satellite communication system is relatively insensitive to large deviations in average message length, average message arrival rate, and aircraft population from forecasted values. The results of this analysis are presented in a parametric fashion so that the channel requirements for various communications loads and transmission rates can also be examined.

3.6 PRELIMINARY MIXED VOICE/DIGITAL COMMUNICATIONS REQUIREMENTS

The previous analysis has been concerned with either an all-digital or an all-voice satellite communication system, and it was shown that an all-voice system requires 40 channels for a transmission rate of one word per second and an all-digital system requires three channels for a transmission rate of 800 bits per second. Since 40 channels is a somewhat larger number of channels to provide for aircraft communications than is desirable, and an all-digital system might not be appropriate as some messages might be sent best vocally, it is of interest to investigate channel requirements for voice/digital systems. Figure 29 presents a list of preliminary alternative voice/digital systems which are believed to represent the most appropriate means of transmitting the aircraft communication messages described in Section 3.3. More refined estimates will be discussed in greater detail in the following section.

Before the number of channels required for each of these alternatives can be calculated, the average message length and average message arrival rate for each of these alternatives must be determined. These calculations are similar to those of Section 3.3.3 with the exception that message types 0 and 8 are considered digital for digital messages and voice for voice messages and are treated accordingly in these calculations. The resulting values for these parameters are depicted in Figure 30.

The voice channel and digital channel requirements for each one of the cases depicted in Figure 29 can now be obtained. The method employed is to solve Equations 15 through 19 in the manner described in Section 3.4 for a voice transmission rate of one word per second and a digital transmission rate of 800 bits per second. The resulting channel requirements for each alternative are presented in Figure 31. The channel utilization rates are also shown in this figure.

Message Type \ Case	1	2	3	4	5	6	7	8
Position report	V	D	-	D	-	D	-	D
Position determ.	V	V	V	D	D	V	V	D
In Flight weather	V	V	V	D	D	D	D	D
Terminal forecast	V	V	V	D	D	D	D	D
ARTC traffic	V	V	V	D	D	V	V	D
Company comm.	V	D	D	D	D	D	D	D
Radio/IFF checks	V	V	V	1/2D	1/2D	V	V	D

V = Voice message
D = Digital message
1/2D = 1/2 digital message, 1/2 voice message
- = No message of that type

Figure 29. Alternative Voice/Digital Aircraft Communication Systems

Case	Average Message Arrival Rate (Messages/Second)		Average Message Length	
	Voice	Digital	Voice (Words)	Digital (Bits)
1	0.44	0	68	0
2	0.25	0.20	62.4	933
3	0.25	0.08	62.4	795
4	0.06	0.41	34.8	946
5	0.06	0.28	34.8	886
6	0.21	0.24	60.4	1033
7	0.21	0.11	60.4	961
8	0	0.44	0	1028

Figure 30. Average Message Length and Average Message Arrival Rates for the Alternatives of Figure 29

Case	Voice	Utilization	Digital	Utilization
1	40	75%	0	0%
2	23	65%	2	12%
3	23	65%	2	4%
4	6	23%	3	20%
5	6	23%	2	10%
6	19	60%	2	10%
7	19	60%	3	19%
8	0	0%	3	19%

Figure 31. Channel Requirements and Utilization for the Alternatives of Figure 29

The results (see Figure 31) show that digital channel requirements are relatively insensitive to the effects of voice/digital message tradeoff as either two or three digital channels are required for all cases where digital communication is employed. Except for cases four and five, where the only voice transmissions are a portion of the Radio/IFF checks, the voice channel requirements of 19 to 23 channels are still relatively high. If it is desired to minimize the number of channels required to provide maximum performance, an optimum system in this respect would require all-digital communication for standard messages, and voice channels allocated only for emergency usage. However, selection of an optimum system depends upon the results of the subsequent system hardware analysis as well as the results of this study.

3.7 REFINED ESTIMATES OF AIRCRAFT COMMUNICATIONS REQUIREMENTS

3.7.1 Refinement of the Analysis

The preliminary analysis was basically a parametric approach using a range of values of input parameters such as voice speaking rates and digital data rates, and examining the sensitivity of the results to variations in input parameters such as average message length, arrival rate, total load, and the like. At the outset, the performance evaluation involved examination of a number of factors, e.g.:

a) Probability of saturation

b) Utilization rate

c) Expected number of messages in a system

d) Expected message time

e) Probability of excessive message time.

As has been brought out in previous paragraphs, examination of these various factors led to the selection of a heuristic optimum number of voice and data channels. As it turned out, the payoff was not in the selection of the heuristic optimum number of channels itself, but was instead, in the understanding of the quantitative relationship between the various input parameters and performance evaluation factors. For example, the heuristic optimum number of voice channels ($C_V = 1$) although based on a "clear channel" service with the probability of saturation of less than 5 per cent still yielded a utilization rate of some 75 percent, a surprisingly high figure for clear channel service. In the final analysis, the selected number of voice channels was based on utilization rate and expected waiting time, as well as probability of saturation or heuristic optimum figure. Also, it was very quickly apparent that, for the relatively low data rates examined, i.e., in the range of 1000 bits/sec, the hardware mechanization of this digital equipment was straightforward at any of the data rates examined; and since the data link bandwidth required was strictly a function of the communication load in bits per second itself, the heuristic optimum concept did not pick the data rate. The digital data rate selection was thus made primarily on a hardware basis*. Finally, the preliminary analysis made it quite clear that the voice channel requirements would design the system, i.e., even if almost all communications were made over data link, those voice communications that would remain would still use

*See Paragraph 4.5.3.

up most of the bandwidth and, therefore, require most of the satellite power. Finally, as a result of the mixed voice/digital communications analysis discussed in Section 3.6, it was possible to select a logical mix of voice and data communications which, it turns out, is a modification of Case No. 6.

The refined communications load analysis described in this paragraph was made in order to describe conditions more precisely around a recommended design approach. Accordingly, the probability of saturation, utilization rate, and expected message time were calculated as a function of the number of voice channels and the number of groups or regions in which these voice channels could be divided. Input parameters were as follows:

- Modified case No. 6 with a new message content:
  - a) Deletion of the radio/IFF check
  - b) A new position report (Autorep - described in Section 4.6.3 of this volume)
- Selected voice rate within the previous range of values: 1.5 words per second
- Selected digital data rates: 1200 bits per second (for the reasons indicated in Paragraph 4.5.3)
- Different regions or groupings were investigated, i.e., combination of Autorep plus weather on a single data channel, with Company on a second data channel vs. Autorep on a single data channel with weather and Company on a second data channel vs. three individual channels for both stochastic and steady flow for Autorep; as well as procedurally dividing up the voice channel into one, two, three, or four sets or groups, called regions.

3.7.2 Digital Messages

Digital messages consist of Company Communications, Weather, and Autorep. The weather message includes both in-flight weather and terminal forecast messages, which in the previous sections were considered to be separate messages. The Autorep message replaces the present Position Report message and has a message length of 280 bits (200 information bits and 80 bits to account for acquisition and synchronization times), an arrival rate of one message every 20 seconds for an

SST, and an arrival rate of one message every 80 seconds for a subsonic aircraft. The digital transmission rate, C_D, is 1200 bits per second.

Company communications and weather can be jointly allocated to a single data channel resulting in an average message length of 1130 bits and an average message arrival rate of 0.09 message/sec. This results in a utilization rate of 9 percent and an expected waiting time of a small fraction of a second. The Autorep messages utilize 73 percent of a data channel not including roll call (ground-to-air) messages. (Note: the roll call messages will be placed on a separate carrier frequency in order to simplify user hardware.)

3.7.3 Voice Messages

The analysis will be conducted for the case where all channels are accessible to the user at any time in the trip, as well as for cases where the number of channels accessible to an individual user at any one time is restricted.

From an efficiency point of view it is b 'er to have all channels accessible to all users so that if one user finds that he is unable to transmit a message on a channel that is busy, he can simply turn to another channel which is not in use and make his call. If he were required to use a particular channel which is assigned to him, he might be forced to wait for some time before his assigned channel becomes free, while several other channels might well be idle. On the other hand, the task of manually searching for an idle channel by turning a selector dial and listening to see if a new channel is idle, could, during busy periods, consume excessive time and energy and prove to be very frustrating to a pilot. This brings to mind various forms of user hardware gadgetry which would provide him with a visual display of the status of each channel or might automatically find the pilot a free channel if one existed simply at the actuation of his mike button. TRW actually had initiated some efforts in the latter direction when the analyses that will be described in the following paragraphs showed such a devise would be unnecessary.

Channel restrictions can be established either by geographical sectioning where specific channels are assigned to all craft within a given region, or by user assignments where individual users are "grouped," i.e., assigned specific channels for a duration of time — perhaps a whole flight. These two cases are mathematically equivalent.

Figure 33 illustrates the probability that the system is busy (saturation), utilization rate, and expected waiting time as a function of the number of channels available for a "single group" case wherein all channels are accessible to all users. It assumes that each user will continue to search for an idle channel (and in fact, assumes that the searching time is zero). The fact that some waiting time is still possible is simply a reflection of the fact that it is possible for all channels to be busy at once.

Before drawing any conclusions from Figure 32, we must analyze the significance of the parameters treated there. The probability of saturation that was shown during the earlier analyses was useful in predicting the point at which additional channels cease to become worthwhile, i.e., the so-called "heuristic optimum" number of channels occurred when the probability of saturation was between 2 and 5 percent. Operationally, however, the probability of saturation was not found to be a particularly useful indicator of system performance. Waiting time, on the other hand, can be immediately understood and when weighed against the importance of the message itself, can be the basis of a very good qualitative judgment. In fact, if urgency, priority, or importance of messages are quantified, then waiting time in conjunction with them could be used in a quantitative way to select and/or allocate channels. Finally, utilization rate is a very important parameter, inasmuch as channel utilization rate is essentially proportional to the amount of time that the air traffic controller at the ground end of the voice link is occupied.

Clearly, one could pick the knee of the curve in a plot of waiting time versus number of channels, which would result in the selection of about 8 channels; but there are other factors which need to be taken into account. As pointed out by Philco in Reference 7, a utilization factor of 50 percent loading for not more than 50 percent of the time has been determined by ICAO to be a desirable channel loading criterion. One

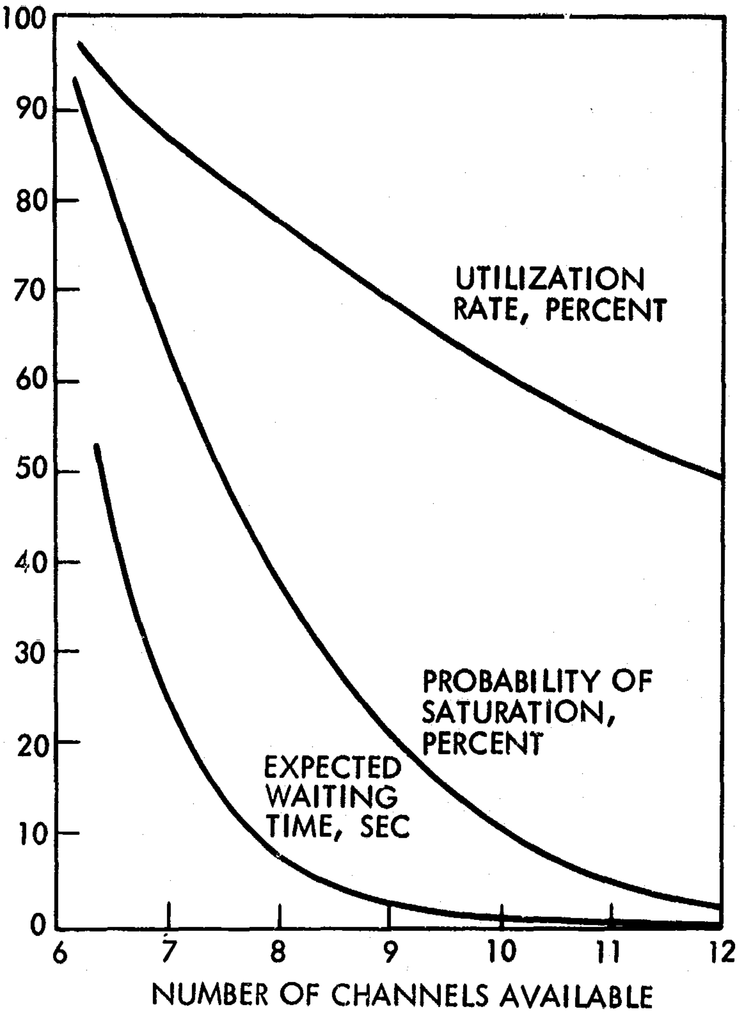


Figure 32. North Atlantic Ocean Area Voice Channel Performance: All Channels Available

might choose to allow transient short-term peaks to reach 80 percent utilization. TRW feels that it is better to design the system nearer to the 50-percent utilization for aviation traffic peaks for the following reasons:

- The system should be able to function in an acceptable level with partial failures, e.g., the outage of a single satellite. The recommended design will function in the event of a satellite outage occurring during a peak traffic condition. In this case higher channel loadings, in the 80 to 90 percent region, will result; but the system will remain operational.

- The additional capability available during off-peak hours and seasons need not be wasted since other users (e.g., marine, search and rescue training, ground point-to-point (ATC and/or commercial) and the like can be used to fill up this capacity. Off-peak hours could also be scheduled for recharging of satellite batteries and the like which might be allowed to drain for short periods during peak traffic hours.

- Studies of this nature continually underestimate growth rate and capacity requirements. Thus, designing for an 80 percent peak utilization rate would probably yield a system that would actually saturate, soon after becoming operational.

The question of partitioning or assigning users to various regions or groups was analyzed. Figure 33 shows the effect in terms of increased expected wait time as a function of the number of groups or regions used for the 190 aircraft case for eleven and twelve channels.

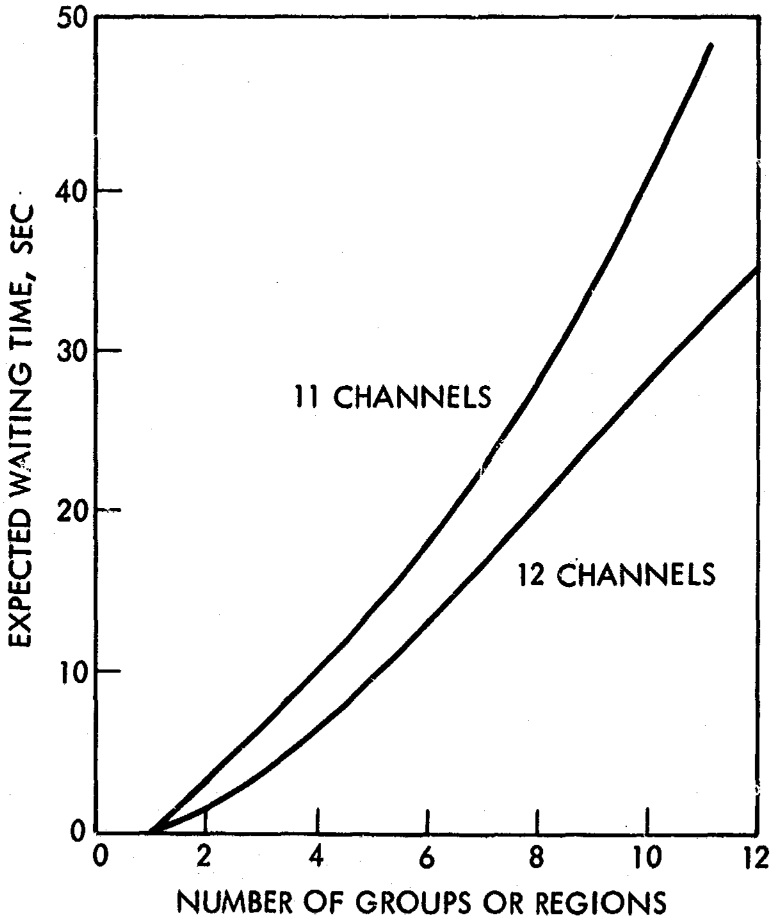


Figure 33. North Atlantic Ocean Area Voice Channel Performance: Channels Grouped (One Channel Available per User)

At first it was felt that it would be better to have all channels available to all aircraft but when the 34-second waiting time associated with the multiple-group, single channel per group approach was weighed against the additional complexity and user hardware required to make a workable single-group, multiple channel system, it seemed clear that the former approach was preferable.

As a result of the foregoing analysis, it appeared that twelve normal voice channels plus one emergency voice channel would be a good design point. In the requirements versus design tradeoffs that ensued, however, it became clear that a total of twelve channels would be far easier to incorporate into the satellite system design since twelve channels can be evenly divided between multiple channels and the difference between eleven and twelve normal voice channels in overall system performance is quite small.

3.8 MARINE MESSAGE ANALYSIS

As was the case in the aircraft message analyses, i.e., Section 3.3, operational communications requirements have to be described in order to obtain estimates of marine message length. Through conversations with people closely acquainted with marine communications, (References 11 and 12), the following list of message types was constructed:

0 Address, Reply, Address, Sign Off, Sign Off
1 Position Reports
2 Position Determination
3 Weather Information
4 Company Administrative
5 Repeats

It is assumed that separate channels will be provided for emergency communications. This list seems to adequately describe, in the majority of cases, the types of messages that will be transmitted to or from ocean going vessels utilizing the Navigation/Traffic Control Satellite System.

3.8.1 Length of Typical Messages

The contents of typical messages of the above types can be found in Figure 34 and are similar to those cited in Refer ... 11. Just as the aircraft messages had a type 0 message associated with them, so does every marine type message. Consequently, the total length of each type message 1 through 5 has to include the type 0 message in order to effect a proper communication. In view of this, a total of 55 words have to be added to the length of each voice type message 1 through 5 in order to obtain the total length of each message.

In the abbreviated representation of messages, the coding methods in use today are postulated. Although the abbreviated messages contain all the pertinent information that is transmitted, there is no exact correspondence between the length of a coded message and that of its voice counterpart. To determine the digital length of each abbreviated (coded) message, the method described in Section 3.3 was employed. The number of bits for each digital message is given in Figure 34.

3.8.2 Estimated Contact Rate Between Marine Vessels and Ground Stations

To analyze the communication loads placed upon the Navigation/Traffic Control Satellite, an estimate of the contact rate for each type of message, (i.e., types 1 through 5) was obtained. For this purpose present marine reporting schemes were examined. For position reports, the American Merchant Vessel Emergency Reporting System (AMVER) is used by approximately 50 to 60 percent of the U.S. vessels in the North Atlantic Ocean (Reference 9). This system requires that ships give a position report once a day at a fixed time, and it is assumed that this contact rate will be adequate for the proposed 1975 system since most transoceanic ships will still travel at close to today's speeds. Hence, this contact rate for position report was used as the baseline rate, as indicated in Figure 35, but it is assumed that 100 percent of the large ships will so report.

The present weather reporting scheme of the U.S. Weather Bureau requires that all U.S. ships transversing major oceanic routes transmit weather data every six hours. This data is then used by the Weather Bureau for updating their weather forecasts for given oceanic regions.

Message	Voice: Typical Message	Word Length	Digital: Abbrev. Mess.	Bit Length
(0) (a) Address	New York Radio this S.S. Mariner Routine message over	11	NMQ DE WTLX R HW K	144
(b) Reply	S.S. Mariner this is New York Radio over	9	WTLX DE NMQ QRK5 Q RV K	184
(c) Address	New York Radio this S.S. Mariner routine position report one eight ze-o zero GMT January two two six eight	21	NMQ DE WTLX R SS MARINER CK 11 22 1800 GMT BT	360
(d) Sign Off	End of message over	4	BT HWK	48
(e) Sign Off	S.S. Mariner this is New York Radio Roger out	10	WTLX DE NMQ R QSL TKS AR	192
(1) Position Report Ship - Shore	Latitude four two dash three zero decimal zero north, longitude six two dash three zero decimal zero west, January two two one seven one five GMT	28	42-30.0N 62-30.0W 22 1715 GMT	232
(2) Position Determ.	We have Nav/Sat fix on you your position is four two dash three zero decimal five five longitude West six two dash two five decimal five latitude North	28	Nav/Sat fix 42-30.5 W 62-25.5 N	232
(3) Weather Info. Ship - Shore	Latitude four two dash three zero decimal five longitude six two dash two five decimal five, two two one five zero zero zero GMT Wind direction nine two degrees, Wind speed ten-kilometers, Sky condition one eight overcast cumulus clouds, visibility five kilometers, Air temperature ten degrees centigrade, Dew point ten degrees centigrade, Pressure change for past three hours plus ten milli-bars, Sea surface temperature five degrees centigrade, Sea condition one meter swells from one zero nine degrees five second intervals	82	20542 59318 46937 81611 37442 99096 12506 81679 11346 (Sample code only)	424
(4) Company Admin. Ship - Shore	Latitude four two dash three zero decimal zero north, longitude six two dash three zero decimal zero west. One five one two January two two Great Circle route Course two four seven decimal zero, speed one five knots, estimate New York two six January one two zero zero GMT. Next report two five January one two zero zero GMT.	63	42-30.0 N 62-30.0W 22 1512 GMT GC 247.0 15.0 ETA NEW YORK 26 1200 GMT NEXT REPORT 25 1200 GMT	736
(5) Repeat	Latitude four two dash three zero decimal zero north longitude six two dash three zero decimal zero west.	18	42-30.0N 62-30.0W	136

Figure 34. Marine Message Lenght Estimation

These weather forecasts are recorded on tapes which are transmitted continuously via radio to the appropriate area. Because of the important impact that weather conditions have on transoceanic navigation, it is assumed that the present requirement for four contacts per day from ocean-going vessels will be maintained for users of the 1975 Navigation/Traffic Control Satellite System. Also, since weather broadcasts from ground stations are sent continuously, it is felt that these weather messages will probably be sent through either a separate channel on the satellite or via radio and are not considered in the communications load analysis (see Figure 35).

Message Type	Marine Vessel	
	Ship to Shore	Shore to Ship
1 Position Report	1 per day	N/A
2 Position Determination	N/A	0.5 per day
3 Weather Information	4 per day	N/A
4 Company Administrative	0.2 per day	0.2 per day
5 Repeats	0.2 per day	0.2 per day

Figure 35. Estimation of the Number of Contacts per Day for Marine Vessels

The remaining contact rates for the different message types were obtained through conversations with people familiar with marine communications (see References 11 and 12). Figure 35 summarizes the results of these contact rate estimations.

3.8.3 Summary of Marine Message Analysis - Voice Portion

Since the estimates for the maximum number of ships in the North Atlantic Ocean area have been obtained as well as estimates concerning the word length of typical messages and their corresponding contact rate, it is now possible to compute the average length of a random message and also the average arrival rate of marine messages at the satellite.

To determine the average length of a random message, the same notation that was developed in Section 4.3 is employed:

$1/\mu_{Vi}$ = Number of words per type i voice message

λ_{Vi} = Arrival rate of type i voice messages (messages per hour)

$AWPVM_1$ = Average words per voice message of the ship to shore type

$AWPVM_2$ = Average words per voice message of the shore to ship type

TAWPVM = Total average words per voice message of the ship to shore and shore to ship type

where

$$AWPVM_j = \frac{\Sigma 1/\mu_{Vi} \cdot \lambda_{Vi}}{\Sigma \lambda_{Vi}}$$

for j = 1, 2 and i = 1, . . . , 5, corresponding to the two general message categories and the five types of messages. The calculation of the average words per voice message for ship-to-shore and shore-to-ship are summarized in Figures 36 and 37. The total average words per voice message (TAWPVM) is obtained in the same manner that was used in Section 3.3.3. Therefore,

$$TAWPVM = \frac{(AWPVM_1)(13,600) + (AWPVM_2)(13,600)}{27,200}$$

$$= 106 \text{ words per message}$$

To calculate the average arrival rate of messages at the satellite, the following notation was used:

$(T\lambda)_{V1}$ = Total arrival rate of voice messages (messages per hour) of the ship-to-shore type

Message Type	Words per Message $1/\mu_{Vi}$	Messages per Hour λ_{Vi}	$(1/\mu_{Vi})(\lambda_{Vi})$
1 Position Report	83	0.042	3.486
3 Weather Information	137	0.167	22.879
4 Company Admin.	118	0.008	0.944
5 Repeats	73	0.008	0.584
Totals		0.225	27.893

$$\text{Average Words per Voice Message } (AWPVM_1) = \frac{\Sigma(1/\mu_{Vi})(\lambda_{Vi})}{\Sigma\lambda_{Vi}}$$

$$= \frac{27.893}{0.225} = 124$$

Figure 36. Average Length of Ship-to-Shore Voice Messages for Marine Vessels

$(T\lambda)_{V2}$ = Total arrival rate of voice messages (messages per hour) of the shore-to-ship type

TNVMPH = Total number of voice messages per hour of the ship-to-shore and shore-to-ship types

Again, the methodology of Section 3.3.3 was employed for this calculation. Thus, the total number of voice messages per hour (TNVMPH) is:

$$TNVMPH = (T\lambda)_{V1}(13,600) + (T\lambda)_{V2}(13,600)$$

$$= 3563.2 \text{ messages per hour}$$

Message Type	Words per Message $1/\mu_{Vi}$	Messages per Hour λ_{Vi}	$(1/\mu_{Vi})(\lambda_{Vi})$
2 Position Determ.	83	0.021	1.743
4 Company Admin.	118	0.008	0.944
5 Repeats	73	0.008	0.584
Totals		0.037	3.271

Average Words per Voice Message ($AWPVM_2$) $= \dfrac{\Sigma(1/\mu_{Vi})(\lambda_{Vi})}{\Sigma\lambda_{Vi}}$

$$= \frac{3.271}{0.037} = 88$$

Figure 37. Average Length of Shore-to-Ship Voice Messages for Marine Vessels

and the total arrival rate of messages per second is

$$\frac{3563.2}{3600} = 0.99 \text{ messages per second}$$

Now that the total average words per message (106) as well as the total arrival rate of messages (0.99 per second) have been determined, the baseline estimates for $1/\mu_V$ and λ_V are defined. The remaining analyses can now be performed using these estimates in conjunction with Equations 15 through 19.

3.8.4 Summary of Marine Message Analysis - Digital Portion

The average length of a random digital message is found in the same manner as was described in Section 3.3.3. Employing the techniques described therein as well as taking into account the acquisition and synchronization times as described in Sections 3.3.1 and 3.3.2, the total average bits per digital message (TABPDM) for the three transmission rates which were used in Section 3.3.4 were obtained and are listed below:

Transmission Rate (bits/second)	Average Message Length (bits)
75	1414
500	1435
1000	1460

Since the digital message arrival rate is the same as the voice message arrival rate (i.e., 0.99 messages per second), Equations 15 through 19 can now be solved, and channel requirements for marine communications can be determined.

3.9 PRELIMINARY MARINE ALL-VOICE COMMUNICATIONS REQUIREMENTS

The method used to obtained channel requirements by examining the measures of satellite system performance described by Equations 15 through 19 was presented in detail in Section 3.4. Since the methodology for determining marine communication channel requirements is similar, the details of the analysis are omitted in this section. The baseline estimates for average message length, ($1/\mu_V$ = 106 words) and average arrival rate (λ_V = 0.99 messages per second) result in channel requirements of approximately 132 channels for a transmission rate of one word per second and 46 channels for a transmission rate of three words per second.

Figure 38 gives the percentage of time that the system is busy for a given number of channels and given transmission rates. For the case of 132 channels and a transmission rate of one word per second, the percentage of time that the system is busy is 79 percent. For the 46 channel case and a transmission rate of three words per second, the system is busy approximately 75 percent of the time.

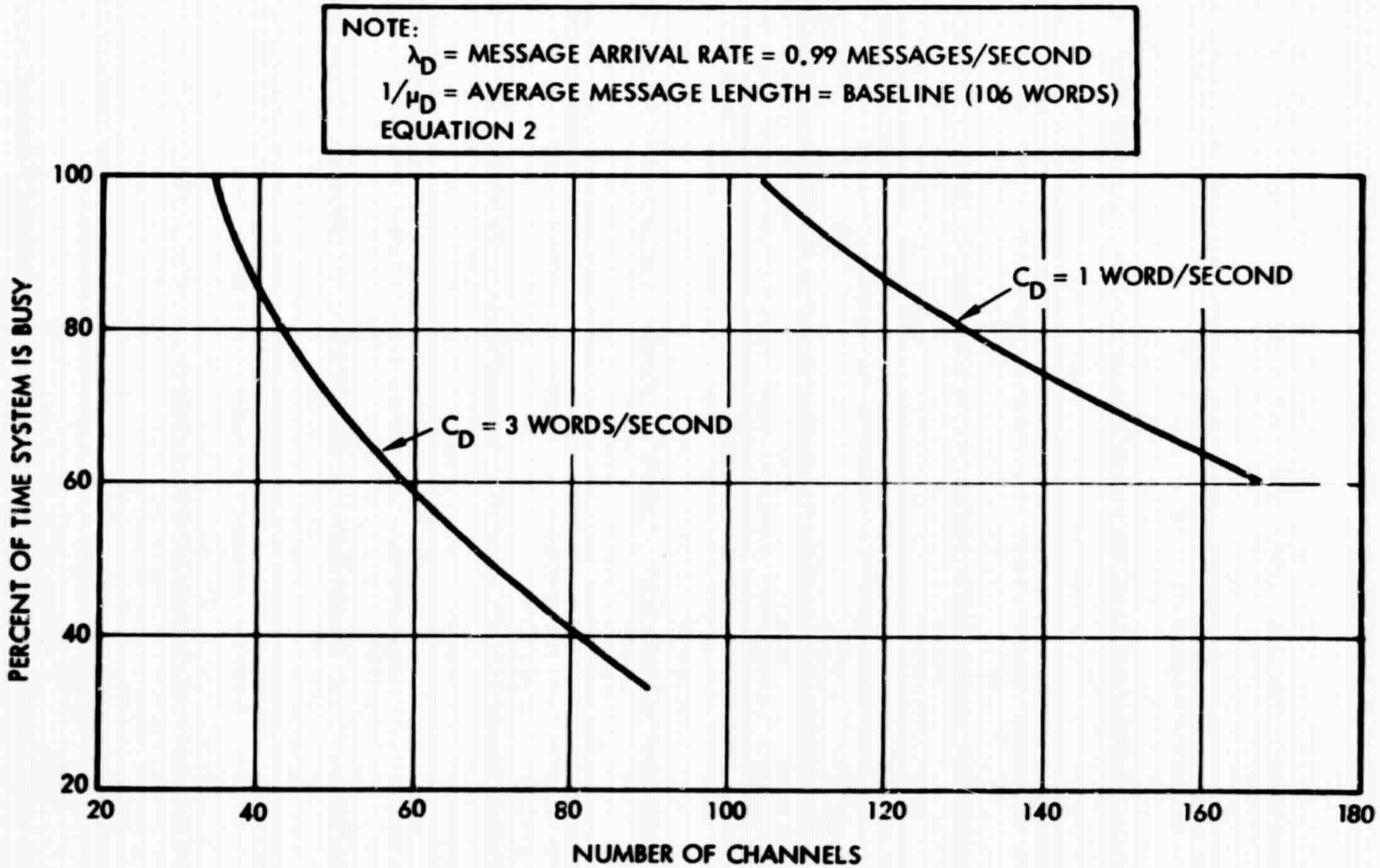


Figure 38. Percentage of Time that the System is Busy

3.10 PRELIMINARY MARINE ALL-DIGITAL COMMUNICATIONS REQUIREMENTS

This section contains the results of an analysis carried out in a manner similar to that performed in Section 3.5. The first step in this analysis was to obtain the effect of various transmission rates upon the required number of channels. The relationship between various transmission rates, number of channels, and utilization rates is shown below and in Figure 39.

Transmission Rate (bits per sec)	Number of Channels	Utilization Rate (percent)
75	27	73
500	7	42
800	5	36
1200	4	30
1200	2	60

This data was used in the Requirements Analysis (Paragraph 2.6.3.1) and in the overall channel allocation discussed in Paragraph 1.3 of this volume.

3.11 COMPUTER PROGRAM DESCRIPTION

To utilize the communication model described in Section 3.1, it is necessary to evaluate Equations 15 through 19. These equations, as is evident from their form, are not easily handled by manual means. Also, since it is desirable to perform sensitivity analyses, other inputs besides the baseline case described herein are needed. This involves parameterization of the variables of interest in Equations 15 through 19 (i.e., λ, $1/\mu$, C).

For these reasons, one of the available on-line computers, the GE 265, was used for this purpose. An output listing of the program shown in Figure 40 essentially represents the coding required to readily solve Equations 15 through 19 in a parametric manner. The program was written in a computer language called Basic and has a running time of approximately 5 minutes per case (i.e., each curve of Figures 16 through 20 takes approximately 5 minutes of computer time to generate).

Number of Regions (Stochastic Message Arrival)	Total Required Number of Channels	Required Number of Channels Per Region	Probability System is Busy Per Region $P(\leq N)$	Utilization Rate Per Region $\rho(\%)$	Expected Time Message is in System Per Region T(sec)
1	2	2	0.46	61	1.93
	3	3	0.14	40	1.32
	4	4	0.04	30	1.24
	5	5	0.01	24	1.23
3	3	1	0.40	40	1.92
	6	2	0.07	20	1.28
	9	3	0.01	13	1.23

Note: Average Message Length $1/\mu$ = 1470 bits

Average Message Arrival Rate λ = 0.99 messages/second

Figure 39. Marine Digital Communications System Channel Requirements

```
10  READ L, M, C1
11  READ L1, L2, L3
12  READ L4, L5, L6
14  PRINT "Z", "D", "T", "N"
15  PRINT
16  PRINT "P1", "E", "R", "T1", "N"
20  FOR N=L1 TO L2 STEP L3
22  LET C=C1*N
24  LET R=L/(M*C)
30  LET S=1
40  FOR N1=1 TO N-1
50  LET S1=((N*R)'N1)
60  LET F=((2*3. 1416)  (1/2))*((N1)'(N1+(1/2)))*EXP(-N1)
70  LET S2=S1/F
80  LET S=S2+S
90  NEXT N1
100 LET S3=(N*R)'N
108 LET A=EXP(-N)
110 LET S4=(1-R)*(((2*3. 1416)'(1/2))*((N)'(N+(1/2)))*A)
120 LET S5=S3/S4
130 LET P0=1/(S+S5)
140 LET P1=P0*S5
150 LET E=(R/(1-R))*(N*(1-R)+P1)
160 FOR T=L4 TO L5 STEP L6
170 LET Z1=N*(1-R)-1+P1
180 LET Z2=((M*C)/N)*T
190 LET Z3=EXP(-Z2)
200 LET Z4=N*(1-R)*P1
210 LET Z5=(1-R)*M*C*T
220 LET Z6=EXP(-Z5)
230 LET Z7=N*(1-R)-1
240 LET Z8=(M*C)/(N*Z7)
250 LET Z=(Z1*Z3-Z4*Z6)*Z8
260 LET T1=N/(M*C)+P1/((1-R)*M*C)
270 LET   D=(Z1*Z3-P1*Z6)/Z7
271 PRINT Z, D, T, N
272 PRINT
273 PRINT
280 NEXT T
282 PRINT P1, E, R, T1, N
283 PRINT
290 NEXT N
300 DATA 1.25, .025, 3
301 DATA 17, 39, 2
302 DATA 1, 33, 4
310 END
```

Figure 40. Computer Program Listing

3.12 REFERENCES

1. Kleinrock, Communication Nets, McGraw-Hill, 1964.

2. Saaty, Elements of Queueing Theory, McGraw-Hill, 1961.

3. RTCA, Current Status Universal Air-Ground Digital Communication System Standards, July 21, 1967.

4. Flying Tiger Line Inc., Form #3157, Rev. 9-55.

5. Aswad, Trip Report - Aeronautical Radio Inc. ARINC., 3313.4-11, March 3, 1967.

6. Aswad, Trip Report - Discussion With Aeronautical Radio, Inc. and FAA Located in the San Francisco Bay Area, 3313.4-8, Dec. 6, 1966.

7. Baker, A First Estimate of the Length of Air-Ground and Ground-Air ATC Digital Messages, FAA Working Paper Project 232-002-020, January 3, 1967.

8. Raizman, Pan Am Plans Digital Encoder System, Electronic News, April 3, 1967.

9. Campbell, J. W., Predicted Operation Requirements For a Non-military Traffic Coordination and Navigation Satellite System, Contract NASW-809, Final Report, Technology Audit Corporation, Washington, D. C.

10. Czubiak, D., Strat-X (Search Radar), 08810-6002-R300, 15 May 1967.

11. Smuczynski and Blum, Trip Report - "U. S. Coast Guard, Long Beach," TRW Report 3414.2-143, 24 January 1968.

12. Smuczynski, Contact Report - Transmarine Navigation Corporation, Long Beach, California.

13. Morse, P. M., Queues, Inventories and Maintenance, John Wiley and Sons, Inc., 1967.

14. Air Traffic, Part II (Staff Report), in FLYING, February 1968.

15. "Systems Engineering Study of Aeronautical Satellite Service," Final Report to Communications Satellite Corporation, Philco-Ford Corporation, et al, TR-DA1583(1), 15 December 1967.

16. TRW, Advanced SST Guidance and Navigation Systems, Vol. II, Contract No. NAS12-510, 1967.

PRECEDING PAGE BLANK NOT FILMED.

4. COMMUNICATION SUBSYSTEM ANALYSIS

4.1 INTRODUCTION

The communication subsystem portion of the study was divided into two principal efforts: an analysis of the key communication parameters and a preliminary design of the communication link including block diagrams of the user's equipment and the satellite transponder. All the results except the detailed transponder design are discussed in this section. The communication analysis was designed to explore the sensitivity of key design parameters, e.g., carrier frequency, modulation formats, etc. Once these parameters were evaluated and the trade-offs among them well understood, detailed communication link design was performed in the final phase of the study. The analysis was limited to those aspects of the communication subsystem that can significantly alter link performance. Its major elements were the carrier frequency, the aircraft terminal parameters, the satellite transponder and antenna characteristics, and the appropriate modulation formats.

4.2 ANALYSIS OUTLINE

4.2.1 Basic Approach

The approach used in this communication analysis is shown pictorially in Figure 41. Basically, three independent investigations were conducted to provide inputs to an analysis of the uplink and downlink power budgets at the frequencies of interest. These budgets were used as the tool to integrate the results of all the separate studies. They aided in identifying key assumptions, deficient empirical data, and critical equipment parameters. The technology forecasts were aimed at predicting both satellite and aircraft terminal performance in 1975. Such characteristics as satellite and aircraft antenna gain, receiver noise, and transmitter power were investigated and estimated. The propagation analysis provided an insight into the transmission anamolies at the three candidate frequencies, viz., VHF, UHF, and SHF. The purpose of the modulation study was to identify promising techniques and formats which would provide the necessary efficiency in the satellite links. For voice, FM using either discriminator detection or a phase-lock loop demodulator was explored. The use of voice processing, i.e., filtering, clipping, etc., was also considered. For digital data, coherent phase shift keying (CPSK), differential phase shift keying (DPSK), and frequency shift keying (FSK) were considered.

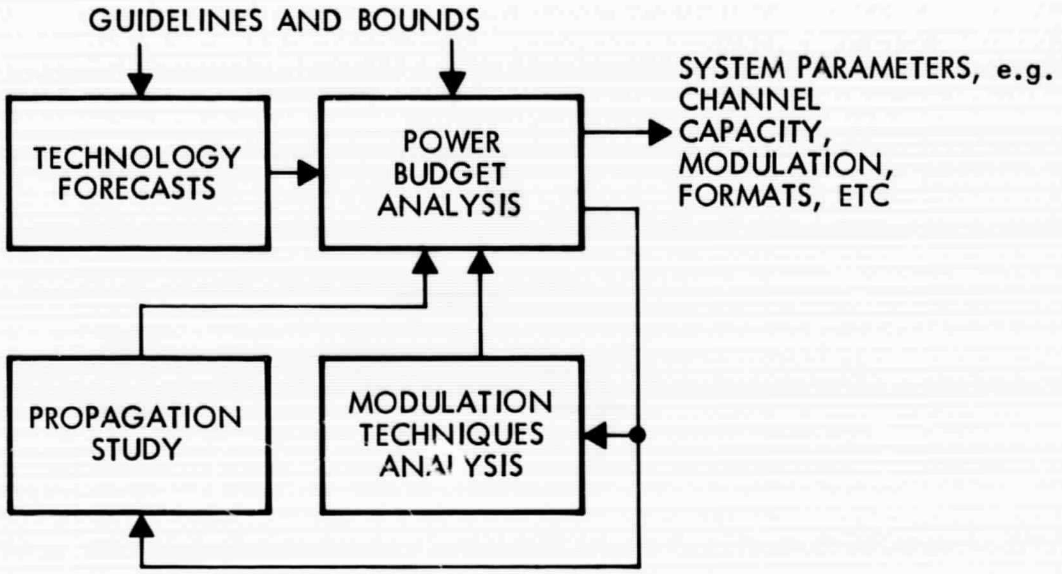


Figure 41. Communications Subsystem Analysis Outline

A prime result from this analysis was an estimate of satellite channel capacity for the three frequencies of interest. These capacities could then be compared to the requirements derived from the communication load analysis to provide an indication of the ability of the satellite system to satisfy the message demand. The analysis also produced a set of parametric variables that were useful in comparing alternate system configurations and equipment implementations.

4.2.2 Ground Rules and Constraints

A satellite configuration had to be chosen to allow the preliminary budget analysis to be performed. It was assumed that an equatorial synchronous orbit and the maximum satellite antenna gain consistent with coverage of the North Atlantic Ocean area specified in the study ground rules would be used. This coverage question is discussed in considerable detail in Section 7.

The user bounds were based primarily on operational considerations. It was postulated that the antenna would have an aerodynamically-clean design. This meant for a subsonic aircraft it would have a low profile, while in SST aircraft it would be flush-mounted.

The only restrictions placed on the modulation formats deal with analog voice. Intelligible speech rather than speech recognizability was used to define acceptability. Speech processing can, therefore, be used to increase modulation efficiency. Such techniques as band-limiting and clipping were allowed under this criterion.

The guidelines are rather conventional and do not seriously restrict the general applicability of the analysis. Changing these will obviously affect system design but not necessarily the parametric variables based on the design. In any case, these arbitrary ground rules could have been readily changed, if in optimizing the system or link performance, it had become clear that they are unduly restrictive. Such was not the case, however, and all of the above postulates were incorporated in the system design after the analysis verified their merit.

4.3 PROPAGATION INVESTIGATION

4.3.1 General

Power budgets contain two basically dissimilar transmission variables. One type of variable is deterministic and almost time-invariant. It refers to both equipment configuration and certain well-defined losses. These variables include EIRP, receiver antenna gain and noise figure, free-space path loss, and circuit losses. The second form of variable is highly indeterminate and best expressed as a stochastic process. These random variables include atmospheric absorption, ionospheric scintillation, multipath losses, and cosmic and atmospheric noise.

Several sporadic propagation anamolies exist, especially at VHF frequencies, whose occurrence can severely degrade the transmission link. Two of these random link variables are associated with occasional atmospheric and ionospheric disturbances. The third, due to multipath, is a function of the aircraft antenna pattern, the elevation angle of the satellite, and the nature of the terrain being overflown.

4.3.2 VHF Propagation

From a propagation viewpoint, VHF suffers the most serious limitations of the three frequency bands of interest. Both atmospheric absorption and ionospheric scintillation contribute losses to the link. In addition, cosmic and atmospheric noise are higher at VHF than at L-band and C-band. Limited experimental evidence exists on the severity of these individual effects. The ATS voice tests (Reference 1) have provided some additional information on the magnitudes of some of these phenomena, but these tests were limited to mid-latitude flights where the full effects are not observable. Further testing is required, especially in the North Atlantic Corridor which is on the fringe of the high-loss auroral zones to establish the margins necessary for operational usage.

4.3.2.1 Ionospheric Scintillation

Scintillation is caused by irregularities in the electron content of the ionosphere due to variable solar activity. These irregularities will produce occasional fading in the received signal level. The fading can be either slowly-varying quasi-periodic, with a period of 5 to 10 minutes, or rapid with fades as short as 10 to 14 seconds.

There are several theoretical models which aid in predicting the effects of scintillation, but usually empirical results provide best estimates of scintillation. A series of tests were conducted by the Air Force Cambridge Research Laboratories (AFCRL) in 1965 using VHF transmissions from INTELSAT I (Early Bird) (Reference 1). The results of 2280 hours of this data is summarized in Figure 42. This data was recorded for an elevation angle of 25 degrees and a sunspot number of 50. The figure shows that 90 percent of the time the signal was unaffected by scintillation. Although this effect initially appears small, there is one caveat. The AFCRL tests were conducted during a relatively quiet sunspot cycle, and the effects of more disruptive solar activity must still be investigated.

More recent telemetry test results by AFCRL show a more severe degradation, no doubt due to higher solar activity. The results of these

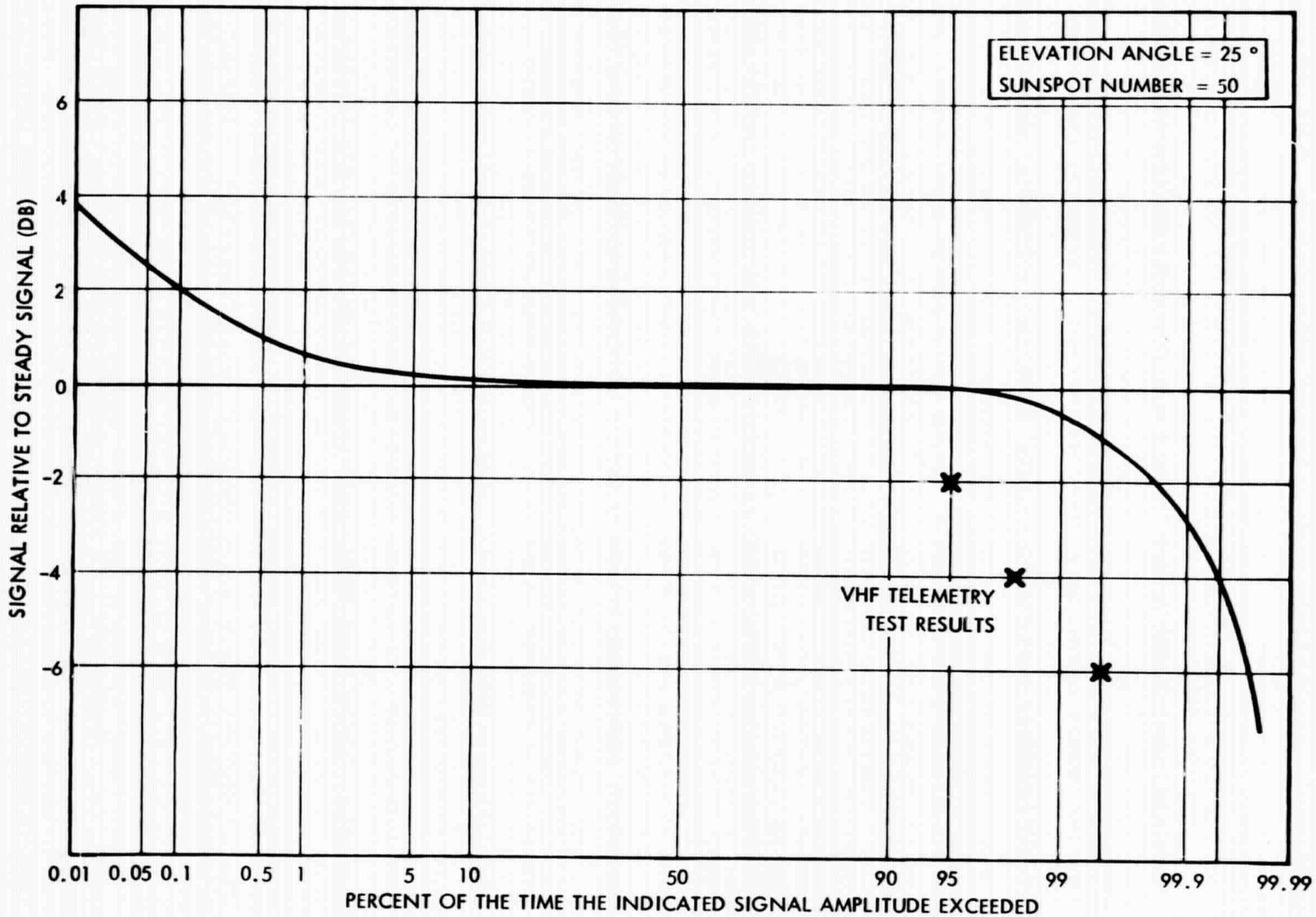


Figure 42. Ionospheric Scintillation of INTELSAT I VHF Signal

tests are also shown in Figure 42. The ATS tests showed variations of signal strength that averaged about 3 db and were most likely due to scintillation.

4.3.2.2 Ionospheric Absorption

Although absorption in the normal ionosphere is usually insignificant at VHF, some attenuation can occur due to polar cap and auroral phenomena. These effects are particularly severe at higher latitudes. These events produce random absorptions with varying durations.

Polar cap absorption is associated with major solar flares. It occurs ten minutes to a few hours after a major flare. Energetic protons emitted by the flare are believed to produce strong ionization in or below the D layer of the ionosphere. The absorption is greater during the day and is observed over the entire polar cap area, north of about 60 degrees geomagnetic latitude. The polar cap events are relatively rare in occurrence. During a year of high sunspot activity, 10 to 12 events can occur, while during minimum sunspot numbers, an entire year can pass without any events. A more likely form of attenuation is auroral absorption which is usually associated with local geomagnetic storms and visible auroral activity. The effects of both these phenomena are presented in Figures 43 and 44. Both of these curves are plotted for an elevation angle of 20 degrees.

4.3.2.3 Multipath Losses

A much more severe propagation anamoly results from the effects of multipath. The multipath phenomena is due to the fact that the aircraft receives signals both directly from the satellite and indirectly via reflection from the earth's surface. Although the direct wave is the desired signal, the actual received signal is a combination of both the direct and the reflected wave. Amplitude and phase variations occur on the direct signal as a result of the reflected wave interfering with the direct signal. Since the phase and amplitude of the reflected wave is a function of both the geometry and the reflection surface, both of which are constantly changing, the exact effect on the direct signal due to this interference is difficult to predict.

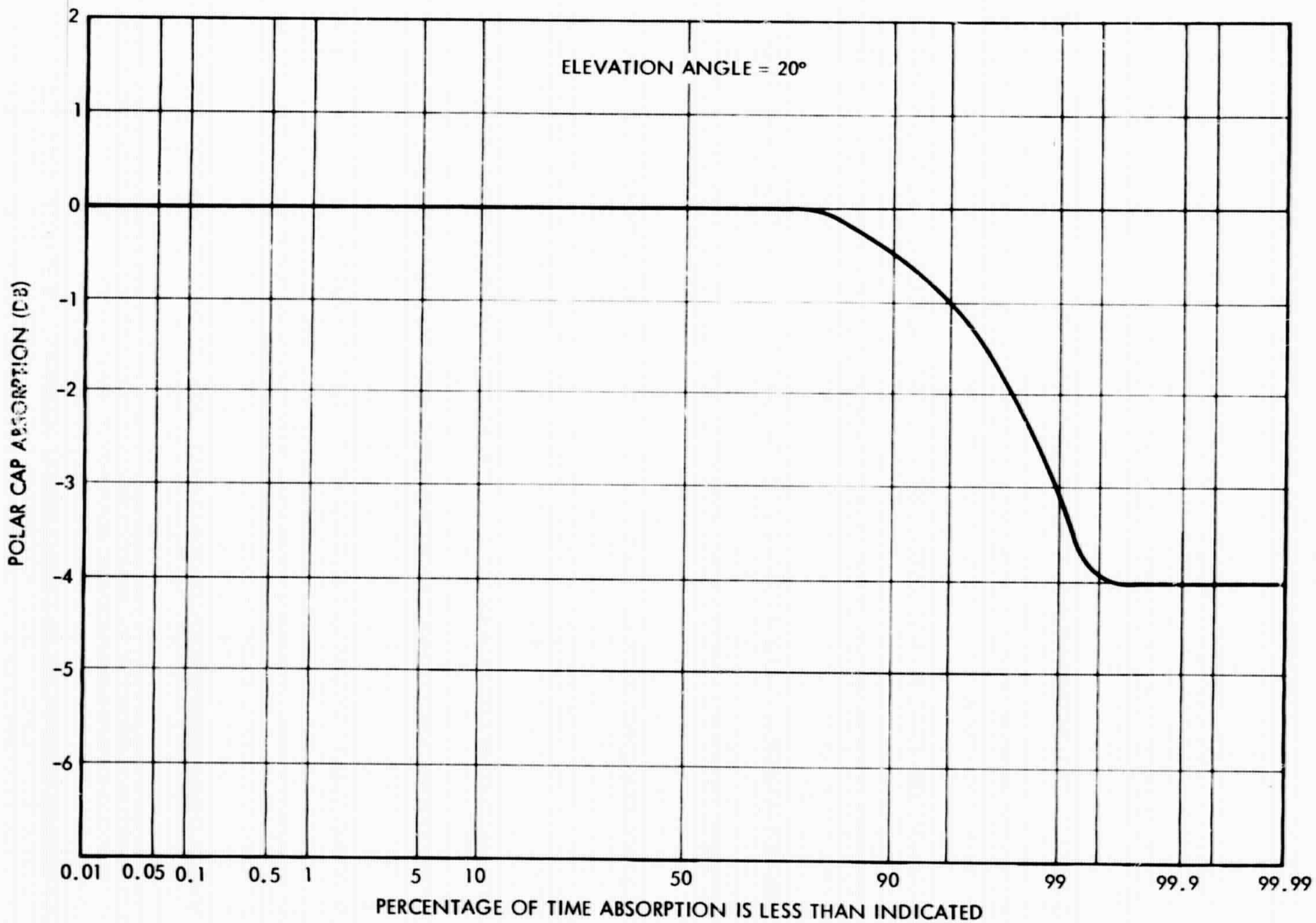


Figure 43. Polar Cap Absorption During Maximum Sunspot Cycle

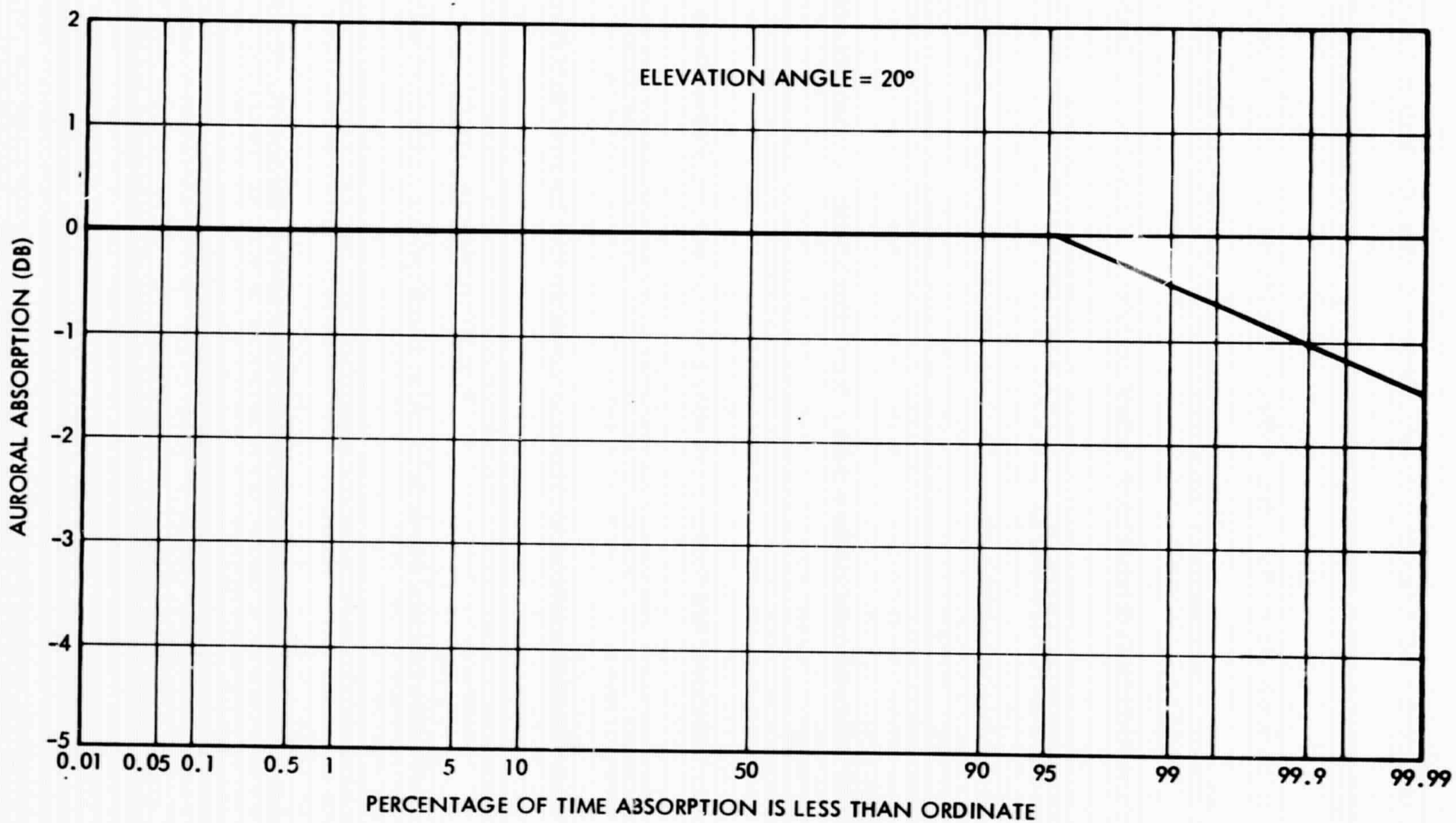


Figure 44. Auroral Absorption Measured at College, Alaska, February 1958

The effects of multipath can be reduced through the use of circularly polarized antennas at both the satellite and the aircraft (Reference 2). This is true because the incident signal polarization reverses at angles greater than Brewster's angles (2 to 5 degrees at VHF) upon reflection, and this phenomenon can be used to discriminate against the reflected ray. Even greater protection can be afforded if the aircraft antenna can be constructed to reject the reflected signal. The multipath losses in this application can be quite severe since the North Atlantic traffic operates at high latitudes resulting in low elevation angles to a stationary satellite. This low elevation angle causes the direct and indirect rays to arrive at the aircraft at similar angles, thereby making antenna discrimination difficult to achieve.

Available data indicates that a smooth seawater model provides an acceptable upper bound on the amplitude of the reflected signal. Using this model, theoretical multipath losses have been calculated by J. L. Levatich of Comsat Corporation (Reference 2). The results are plotted in Figure 45. Data from the ATS tests using somewhat different antenna parameters show that the multipath losses vary from 4 to 7 db (Reference 3). These data were conducted by Collins Radio using the VHF transponder on ATS-1. Data from these experiments indicated multipath fades of less than 4.3 db, 99 percent of the time at 50 to 70 degree elevation angles. At 30 to 50 degree elevation angles an increase to 7.6 db resulted. Effects at lower angles (corresponding to latitudes of 60 degrees) were not investigated. A better antenna design could probably have improved the multipath results by about 3 db.

Based upon both the results of the theoretical calculations of Levatich and the ATS tests, a 5 db signal loss for the effects of multipath fading was assumed at VHF (see Table 12).

4.3.2.4 Total VHF Transmission Degradation

The losses described above must be somehow combined if a prediction of link degradation is to be provided for the VHF power budget. Although this is extremely difficult to perform analytically, one solution has been obtained by Levatich using a Monte Carlo simulation and assuming that the ionospheric and multipath effects are uncorrelated.

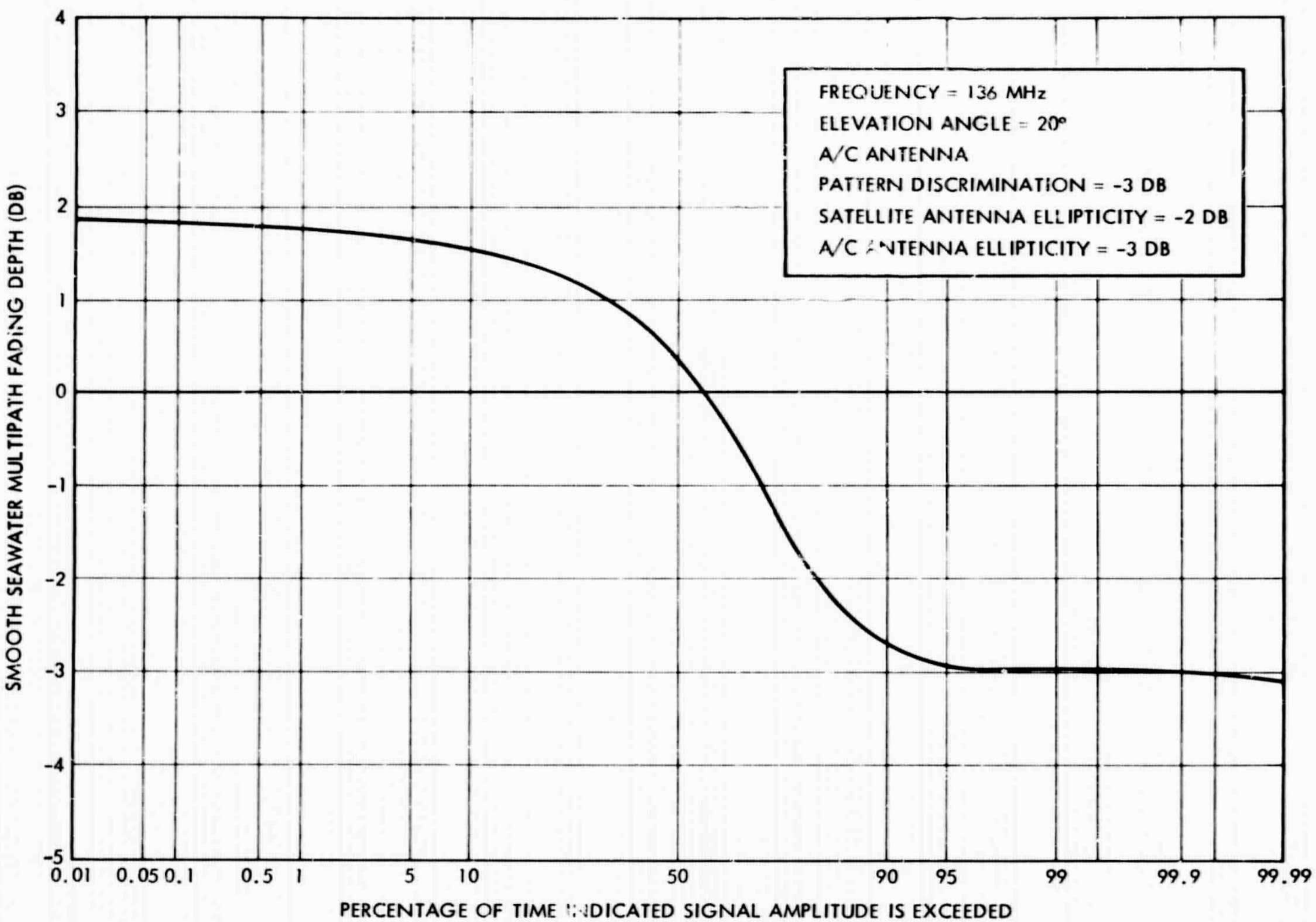


Figure 45. Predicted Multipath Amplitude Distribution

The technique used was to select a random number (multiplied by 100 to obtain a random percentage) and read the value from the graph corresponding to the transmission loss. This was done for each curve and the individual values were added. The entire process was repeated for 25,000 iterations. The value obtained for each iteration was stored, and the number of times a result fell within each range was counted. These numbers were then converted to percentages at the completion of the simulation. The resultant distribution for the combined effects of scintillation, absorption, and multipath is shown in Figure 46. To check the accuracy of this method a run was made for 35,000 iterations, but it did not show any significant deviations from the previous case.

Based upon the limited measured data and the above Monte Carlo simulation, it would appear that a reasonable margin to allow for these effects would range from 4 to 8 db.

4.3.3 L-Band Propagation

4.3.3.1 Atmospheric and Ionospheric Attenuation

Propagation anamolies are significantly reduced at L-band. Although ionospheric scintillation has been reported at frequencies up to 1 GHz, (Reference 4), it is a rare event usually associated with auroral events and for all practical purposes can be neglected. Ionospheric absorption is proportional to the inverse of the square of the frequency (Reference 5) so that at L-band the losses are one-hundredth those at VHF. Atmospheric attenuation is also negligible at these frequencies. Both rain attenuation and cloud and fog absorption are less than 0.02 db (Reference 4). In summary, it appears that propagation anamolies at L-band are very small (on the order of 0.3 to 0.5 db) and, therefore, will not greatly affect the overall path losses.

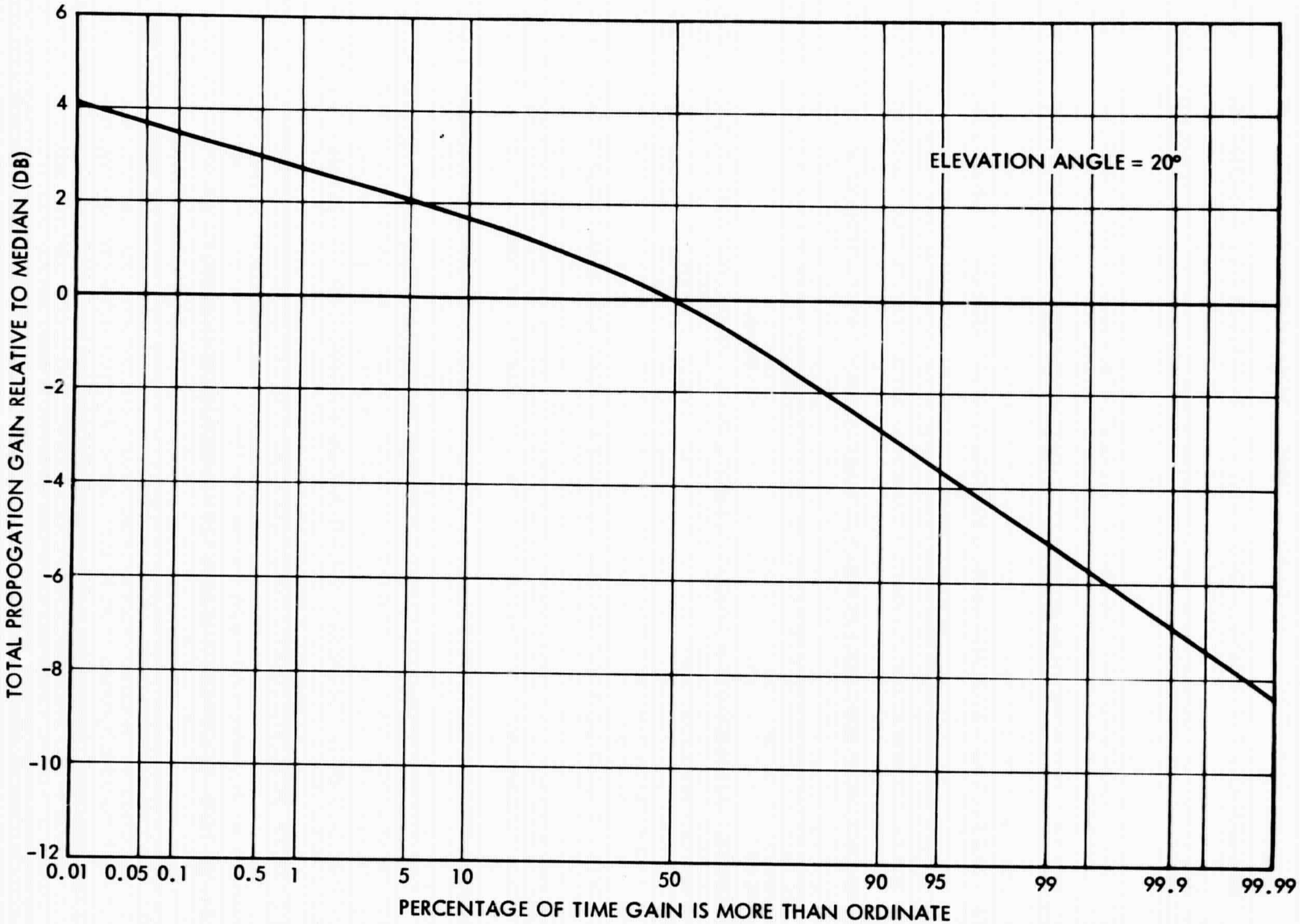


Figure 46. Joint Effect of Transmission Variables

4.3.3.2 Multipath Losses

Multipath should be less severe at L-band because reflection of the signal from the earth's surface tends to become diffuse rather than specular as at VHF. Reflection is specular only for smooth surfaces. Smoothness is defined by the Rayleigh criterion, i.e., reflection is specular if

$$h << \frac{\lambda}{\sin \phi}$$

where

h = rms roughness of the surface

λ = wavelength of reflected wave (0.6 foot at L-band)

ϕ = reflection angle

Only for very calm sea states (waves 1 to 2 feet high peak to trough) does the reflecting surface appear to be smooth at L-band, whereas at VHF sea states ten times higher still appear smooth.

In the presence of multipath, the resultant signal at the receiver will, about half the time, suffer destructive interference between the direct and indirect (ground reflected) rays resulting in a loss of effective gain. In order to study this problem, an extensive series of model aircraft antenna patterns were run (Reference 6) and analyzed for multipath in a special multipath analysis program.

The program, as described in Reference 7, Appendix D, uses complete (3 polarization) pattern measurements to determine the voltage response to an arbitrarily polarized incident ray at elevation angle +E and at the same voltage response to the indirect or multipath ray from elevation angle -E with amplitude and polarization modified by ground reflection. The ground is specified in terms of conductivity, dielectric constant, and rms roughness; but all the data reported here are for smooth sea water and are thus a worst case.

The aircraft model used was a one-fifth scale model F-100. This model was chosen because of its availability and not because it was considered to be a representative aircraft. The data taken with the model should not therefore be considered wholly representative of results that may be obtained with larger aircraft such as the SST or Boeing 707.

Figures 47a and 47b show the probability distribution with azimuth of the resultant multipath ratio at three elevation angles, -10^{o}, -20^{o}, -30^{o}. The distributions were made for 18 points in azimuth (every 20^{o}). The antenna used was a three element slot dipole (see Section 4.4.1.3, L-band antennas). Figure 47a is for the element mounted on top of the fuselage and Figure 47b is for the two elements mounted at 45 degree rolls on each side of the fuselage. The distribution for the 45^{o} mounted dipoles is only over the 180^{o} "favored" sector of azimuth. The multipath ratio is defined as

$$\rho = \frac{\text{Indirect ray voltage}}{\text{Direct ray voltage}}$$

and the resultant signal strength at destructive interference minima is

$$G_{min} = G_{dir.} (1 - \rho)$$

At low elevation angles, the 45^{o} mounted slop dipoles are the only ones of interest since this element of the antenna will be operating in this portion of the sky. From Figure 47b note that for an elevation angle of 20^{o}, 80 percent of the azimuth points result in a multipath ratio of -19 db or more. The corresponding loss of gain at destructive interference minima is then, from the above expression, equal to about 1 db. Therefore, an allowance of 1 db for multipath fading is included in the L-band power budget. For comparison, at 10^{o} elevation the corresponding allowance for multipath fading will be 3.8 db (based on a multipath ratio of 9 db).

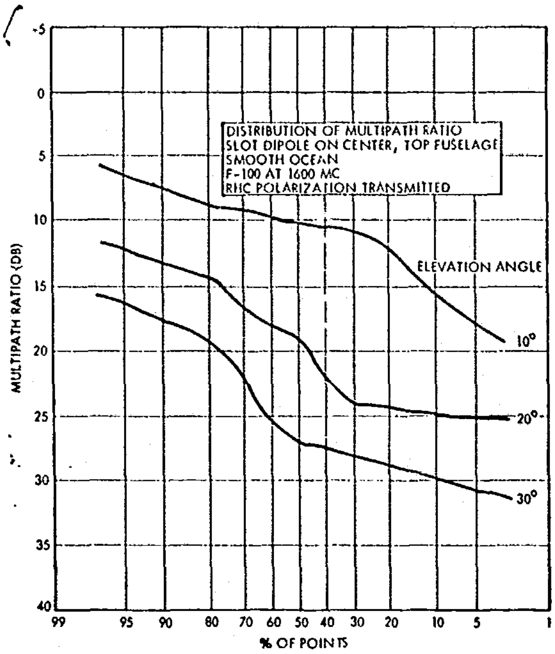


Figure 47a

Distribution of Multipath Ratio
Top Fuselage

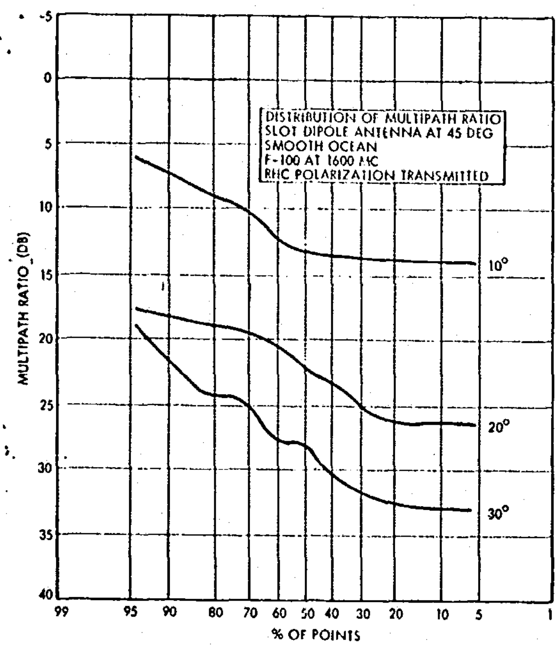


Figure 47b

Distribution of Multipath Ratio,
45° From Top Fuselage

4.3.4 C-Band Propagation

At C-band ionospheric losses are negligible since they are on the order of 1/1000 those at VHF. Atmospheric losses, however, are greatest at these frequencies. Cloud and fog losses are still quite small, less than 0.05 db but rain losses may contribute up to 0.2 db attenuation. Since degradation would be present only in a very heavy rainfall situation (100 mm/hr), the effects of atmospheric absorption can also be largely neglected in evaluating the performance of space communications at C-band.

Due to the increased space loss at these frequencies, an antenna capable of 15 to 18 db is required to provide an acceptable signal level at the aircraft receiver for voice communication. This gain antenna requires the satellite RF power to be very similar to that necessary at L-band. The high-gain antenna and its consequent narrow beamwidth effectively eliminate multipath as a source of transmission impairment. As a result, there is no need to reflect margins for multipath at C-band.

4.3.5 Noise Sources

The effect of radio noise must also be considered in choosing the optimum carrier frequency. This noise is caused by radiation from both natural and man-made sources. Only the natural sources are considered here since little data is available on man-made contributions. Natural radiation arises from extraterrestrial sources, e.g., cosmic and solar noise, as well as from radiation from the atmosphere. Radio noise is frequently described in terms of effective antenna temperature.

There are two types of cosmic noise: background radiation (mainly from the galaxy) and radiation from point sources. Background radiation decreases as the frequency is increased. The variation is shown in Figure 48 (Reference 8). The curve for the maximum noise corresponds to the limiting case when the receiving antenna is pointed to the galactic center while the minimum curve represents an antenna directed toward the minimum noise radiation.

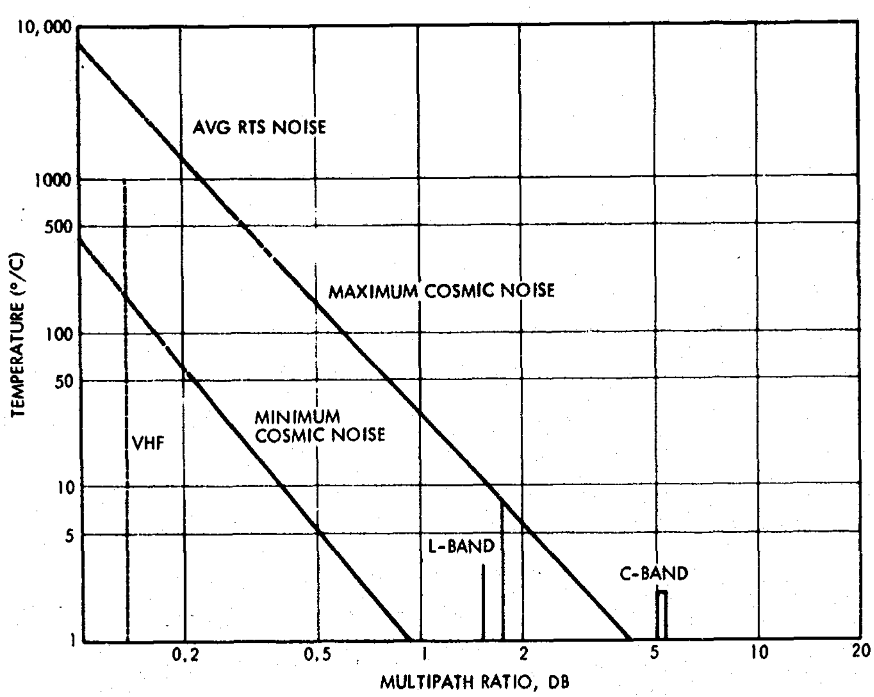


Figure 48. Cosmic Noise and Frequency

Point sources are of very small angular width and in a wide beam antenna contribute little to the overall antenna noise. Since the noise varies inversely with the frequency, VHF represents the worst case. At 136 MHz, the cosmic background noise varies between 200 and 4000°K while at L-band it is only at the maximum approximately 10°K.

The sun also contributes radio noise although it may not contribute significantly to the overall receiving antenna noise due to its small angular width unless the antenna is directional and views the sun. Solar noise is dependent upon the frequency and the degree of solar activity. The apparent noise temperature of the quiet sun is shown in Figure 49 (Reference 7). Since the sun subtends a plane angle of about 1/2 degree, the temperature of Figure 49 would be observed with an antenna whose beamwidth is not greater than 1/2 degree when the beam is directed at the sun. For the wide beam antennas considered for the ATC application (e.g., 98 to 180 degrees), the temperature of the preceding graph must be reduced by a factor of 10^4 at VHF and 10^5 at L-band. At VHF, therefore, effective solar noise can be expected to be approximately 200 degrees while at L-band it is negligible (approximately 2°K). At C-band directional antennas looking toward the sun will see significant temperatures depending on the beamwidth.

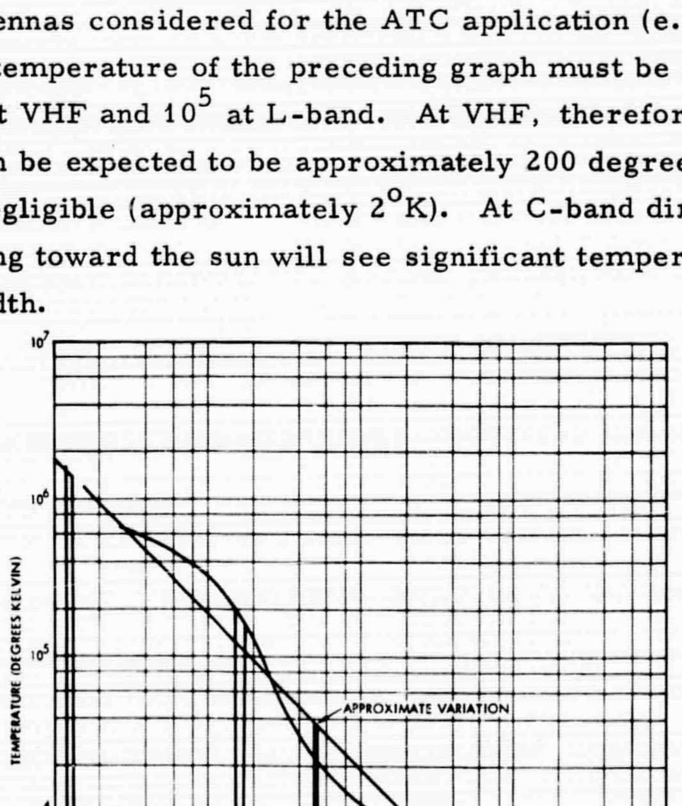


Figure 49. Solar Noise Versus Frequency

Few noise measurements have been made by aircraft receiving signals at the frequencies of interest. The ATS tests measured effective antenna noise temperatures of between 289 and 2135°K with an average of 1005°K.

Antennas looking at the earth from the satellite see a combination of the earth's temperature, cosmic noise temperature, and solar noise depending on the antenna beamwidth. If the antenna just covers the earth, the apparent temperature will be that of the earth, 290°K at all frequencies. As the antenna beamwidth increases, the effective temperature will rise at VHF frequencies because of cosmic and solar noise contributions and will fall somewhat below peak VHF levels at UHF and SHF.

4.4 TECHNOLOGY FORECAST

4.4.1 Aircraft Terminal

The aircraft terminal is the key limitation to the use of a ground-satellite-air communications relay system. Three critical components (the transmitter power amplifier, the low-noise receiver preamplifier, and the antenna) will be discussed here. The other components (viz., the modems, display equipment, etc.) are all well within the present state of the art and, therefore, can be readily provided to suit this application.

4.4.1.1 Transmitter Power Amplifier

The following is a description of several RF power amplifier devices that can be used for amplification in both L- and C-band frequencies. All the different types of amplification systems described here require some form of cooling for the high power stages.

Klystron Amplifier. Although klystrons can be tuned over a relatively wide band, their operational bandwidth at any one setting is very narrow. Klystrons are high, efficient amplifiers having gains of 20 to 40 db and achieving efficiencies of 45 to 55 percent. These devices are available in both L- and C-band frequencies with continuous wave (CW) power capabilities from a few milliwatts to kilowatts. Their best application is as a fixed (or slowly tuned narrowband RF frequency amplifier.

Solid State Amplifier. At this time a number of companies are working on transistor RF power amplifiers for both narrow and wideband application. These amplifiers cover a range from a few MHz up to operating frequencies into the S-band region capable of tens of hundreds of watts. The approach used by most of these works, to obtain high powers, is to combine a number of transistor RF modules into one amplifier. The combining of modules has been accomplished by the use of several different types of hybrids.

The individual module power varies from about 10 to 50 watts. Combining is usually grouped as 2^N modules (i.e., in groups of 2, 4, 8, 16, etc.). Other combining numbers are possible but usually there is a slight, additional loss associated with the technique. Combining modules offers improved reliability since the failure of one module in a group would only degrade the power output by one and one-half times the power of the lost module. Although the efficiency of a module may be as high as 55 to 65 percent, the overall efficiency of an amplifier ranges from 40 to 45 percent. These amplifiers can be made more linear at a loss of efficiency in the system. Odd order intermodulation (IM) products of over 20 db have been achieved in some amplifiers. At lower frequencies (i.e., 2 to 30 MHz) amplifiers capable of over one kilowatt of power have been constructed.

Power amplifiers capable of hundreds of watts at L-band are still in the research and development phase. In less than one year there should be L-band amplifiers that can produce 300 watts and by 1972 this power should be increased to above 500 watts.

Solid state power amplification in C-band is possible but not with present day transistor technology. In order to achieve solid state C-band power amplifiers it will be necessary to use some form of varactor multiplier. A transistor amplifier operating at a lower frequency would be used to drive this multiplier. The overall efficiency of the amplifier must be lower than given above for the transistor amplifier by itself since there is a conversion loss when multiplying a frequency. Again, module techniques can be applied to this amplifier and it should be possible to achieve over 300 watts of output power with about 25 percent efficiency. One other point should be noted, that is, that these are single signal amplifiers with limited dynamic ranges. This type of amplifier is basically a CW system capable of handling only FM, PM, FSK, etc., type of modulation.

TWT's require a magnetic field to focus the beam along the length of the tube. At low and medium powers this focusing can be accomplished with the use of periodic permanent magnets (PPM). At higher powers it is necessary to use electrical solenoids.

The PPM octave TWT amplifiers have rated efficiencies from 25 to 35 percent. With the special narrowband tubes this efficiency is increased to over 50 percent. It should be noted that the high-efficiency tubes, although they have a 20 to 30 percent bandwidth, are basically single signal CW amplifiers. When electrical solenoids are used as for the higher power amplifiers the overall efficiency drops to about 15 percent.

The medium power CW tubes of today using PPM are available in powers of from 100 to 150 watts and up to one kilowatt when electrical solenoids are used. Their gains are generally from 20 to 35 db and some tubes permit multisignal amplification with intermodulation products (IM) better than 25 db. IM products of this amount can only be obtained by operating the tubes at least 4 db below its saturated powers. The L- and C-band PPM tubes weigh about 10 pounds and are about 12 inches long. These tubes require special power supplies which must be taken into account when discussing the weight and volume of TWT amplifiers. With a 400 cycle prime power source this TWT supply would weigh about 40 pounds and have a volume of at least 1.5 cubic feet. It is expected by 1972 that the upper limit of the TWT PPM power levels will be increased to about 300 watts.

Vacuum Tubes. Vacuum tube amplification is possible to frequencies of about 3000 MHz. These higher frequency RF amplifier tubes are constructed to form part of a coasial line. The plate-to-grid-to-cathode spacing of these tubes are very critical and care must be taken in their construction to minimize the drift space between these tube elements. Some of these tubes are used as high power pulse amplifiers but low duty factors must be used. In CW operation they are capable of only a few hundred watts of output power. No large improvement or change in this type of tube is seen by 1972.

4.4.1.2 Receiver Preamplifiers

Present transistor preamplifiers are available at VHF that possess noise figures of 1.5 to 3 db (Aertech 1217L). The noise figure of the preamp used in the ATS tests was 2.0 db (Reference 3). The performance of these devices is quite satisfactory for voice communications, and it can be expected that improvement in reliability will further increase their usefulness.

It is expected that by 1975, transistorized L-band preamplifiers will be available that possess similar noise figures (2 to 3 db) (Reference 9). At present, tunnel diode preamps are available that provide a 3.7 db noise figure (Aertech T4604). Existing transistor L-band preamps have a somewhat higher noise figure, i.e., 4 to 5 db (Aertech 4503, International Microwave Series H).

The C-band preamplifier presents a somewhat more complex problem. Transistor amplifiers will not be available at this frequency by 1975. It is expected that tunnel diode amplifiers can be provided, possessing noise figures at approximately 4 db. At present this type of preamp has approximately a 5 to 6 db figure. If a lower noise figure is required, it is expected that by 1975 reliable uncooled parametric amplifiers will be available with noise figures of 3 db or less. However, operating a preamp in an aircraft environment may prove difficult because of temperature problems with these units.

4.4.1.3 Antennas

VHF Antennas. VHF antennas have been developed for satellite communication and have been tested extensively in the ATS program. Two antennas (the Dorne and Margolin DMC-33-2) and the Bendix ANA-42A are circularly polarized with a minimum gain of zero db. The antennas are manually switchable to provide two radiation patterns. The zenith mode is used for elevation angles between 30 to 90 degrees while the azimuth mode is used for 0 to 30 degree elevation angles. Both of these antennas are satisfactory for voice communication, although improvement in their multipath rejection characteristics would be desirable.

L-Band Antennas. Low-gain antennas covering the upper hemisphere and operating at L-band have been developed and tested extensively by TRW for other programs (References 6 and 10). Figure 4-10 shows the antennas tested. For the ATC communication application with supersonic aircraft, the three-element slot dipole configuration is the most applicable. This antenna provides a minimum 3 db gain over a 160 degree cone and is flush-mounted. However, selection of the correct element from the three is required to obtain the full 160 degree coverage. This switching can be done automatically by signal strength sensing in each of the three elements or by a prior knowledge of the satellite position.

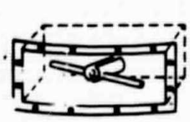
Type	Radiation Pattern	Gain	Axial Ratio (db)	Mounting	Dimension
Curved Dipole Turnstile 	Hemispherical	-3 to 4 db Over 160° Cone	<5	Low Profile	Hemispherical 2-1/2 in. Height 3 in. Rad
Conical-Log Spiral 	Hemispherical	-3 to 5 db Over 160° Cone	<5	Medium Profile	Cone Shape 7-in. Height
Slot Dipoles (Three Required) 	Hemispherical	0 to 6 db Over 160° Cone	<5	Flush	7 x 2.5 x 1.9 in.

Figure 50. User L-Band Antenna Configurations

High-gain antennas using steerable phased arrays have been studied in the range of 6 to 16 db gain for the ATC application (Reference 12). With present state of the art these antennas are both too heavy and costly for aircraft application and are therefore highly undesirable though their directivity would both ease multipath problems and reduce satellite ERP.

Future improvements in weight and cost can be expected which can make phased arrays more attractive for aircraft application. However, for present purposes the system will be designed to operate with the much more practical low-gain hemispherical coverage antenna.

4.4.2 Satellite Communication Subsystem

The two major constraints that satellite technology impose upon an aeronautical comsat are antenna gain and transmitter power. At VHF the antenna problems predominate, while for UHF and higher transmitter efficiency predominates. Because of their size limitations, VHF antennas are presently limited to broadbeam arrays.* A gain of approximately 16 db at beam-edge can be obtained from a squinted 16 x 8 degree beam. However, this provides less than earth coverage at synchronous altitudes, but is suitable for North Atlantic coverage. If it is desirable to use narrower beam antennas, e.g., to limit interference to terrestrial systems, some type of unfurlable design may prove practicable. At L-band and higher frequencies, antenna size is not a major factor and beamwidths from 20 to 5 degrees can be supplied. Achievable antenna gain for these beamwidths range from 16 to 27 db at beam-edge. Antenna design involves a tradeoff between coverage (beamwidth) and gain. The details of the L-band satellite subsystem are discussed in Volume II, Section 2.3.2.

4.5 MODULATION ANALYSIS

4.5.1 General

The basic system requirement for aeronautical comsat service is to provide analog voice and data communications between a traffic control center and an aircraft via a satellite relay. The analysis will be primarily concerned with the link from the satellite to the aircraft (downlink) since it is the critical link in the system The analysis is also based on the use of L-band for the voice and data transmission. The following three modulation techniques were investigated:

*Although 28-30 ft deployable dish antennas are being considered for use on satellites, the size of present VHF antennas limit the antenna configuration to that of a broad beam array. In the future this limitation may be eliminated by the use of such deployable dish antennas.

- Two separate L-band carriers modulated by voice and data, respectively

- One unified L-band carrier phase-modulated by two sine wave subcarriers which, in turn, are modulated by voice and data, respectively

- One unified L-band carrier directly phase-mounted by a square-wave subcarrier (split-phase data) and by a single sine wave subcarrier modulated by voice.

The information baseband consists of one analog voice channel and one 1200 bps digital data stream. A 24-db test tone output signal-to-noise ratio for the analog voice and a bit error rate of 10^{-4} for the digital data have been established as the desired signal output qualities. The basic approach used in the modulation tradeoff study was to determine the required carrier-to-noise density for each service and then translate these ratios into the total carrier-to-noise density ratio required for each of the three modulation techniques above.

4.5.2 Voice

In providing aeronautical comsat service, a more efficient analog modulation technique than the present VHF ground-based communication technique (double sideband-amplitude modulation) is necessary. Considerable effort has been expended in studying suitable modulation techniques (References 11, 12, 13, 14), with the general agreement that some form of angle modulation (PM or FM) should be used.

The use of single sideband amplitude modulation (SSB-AM) is also a candidate modulation technique but does not appear to be as attractive as angle modulation with threshold extension. Angle modulation generally trades wider bandwidth for increased efficiency over amplitude modulation. However, with the use of appropriate peak clipping, the efficiency of SSB-AM becomes competitive with angle modulation. The primary disadvantages of SSB-AM are the requirement for a linear transmitter and the large peak-to-rms ratio in the signal. For the frequency band of interest (L-band) a TWT transmitter is the likely choice. The prime power requirement for this device is a function of peak output power rather than average power. Therefore, considering the transmitter peak power and linearity requirements for SSB-AM, angle modulation appears to be the better of the two techniques.

Further detailed investigation of modulation and speech processing techniques has not been considered appropriate. All communication satellite repeaters currently being utilized are designed for angle modulation and for good reason. Thus, the chosen approach of FM with threshold extension is considered to be near-optimal for the Navigation/Traffic Control Satellite application. Appendix A shows an analysis of single channel FM voice using a phase lock loop demodulator for threshold extension. If appropriate audio processing is included as advocated by almost all of the previous studies, modulation efficiency can be increased at the price of degraded voice quality (although not intelligibility). Consequently, the voice signal is filtered to a 3 kHz bandwidth and peak limiting is used to limit the voice peak-to-rms factor to 7 db.

From Appendix A, a full load test tone rms signal-to-noise ratio of 24 db at the receiver output requires at the input a carrier-to-noise spectral density ratio of

$$\left(\frac{C}{\Phi}\right)_T = 47 \text{ db-Hz}.$$

and the RF bandwidth required is

$$B_{RF} = 24.5 \text{ kHz}$$

4.5.2.1 Articulation Index and Output Test Tone-to-Noise Ratio

The link between articulation index (AI) (and consequently speech intelligibility) and test tone-to-noise ratio requires a precise definition of AI in terms of the available speech power and also a connection between the test tone-to-noise ratio and the speech power at some test tone frequency.

In describing the AI, speech power spectrums are derived for the peak, average, and minimum speech power as a function of frequency (Reference 15). No consideration is given to the percentages of time for which these peaks and minima occur. By definition the AI is unity if the complete range of power between the maxima and minima is available to the listener. If any of this speech power is masked by noise or truncation at some frequency (such as 3 kHz) then obviously the AI will be less than unity.

The articulation index is defined as that fraction of the total power in the speech spectrum which is available to the listener. In addition, Reference 16 demonstrates that the total speech power (assuming 3 kHz truncation and 6 db clipping) is approximately 28.8 db greater than the mean speech power in a 1 Hz bandwidth at 500 Hz. Therefore, the mean speech power-to-noise density ratio at 500 Hz is related to the total speech power-to-noise density ratio by:

$$\left(\frac{P_{sm}}{\Phi}\right)_{500} = \left(\frac{P_{st}}{\Phi}\right) - 28.8 \qquad (20)$$

In an FM system the output rms test tone-to-noise ratio is given by

$$\left(\frac{S}{N}\right)_{tt} = 3\left(\frac{C}{\Phi}\right)\left(\frac{\Delta f}{f_t}\right)^2 \frac{1}{f_m} \qquad (21)$$

where

$\frac{C}{\Phi}$ = predetection carrier-to-noise density ratio

Δf = RMS deviation of the carrier by test tone

f_t = tone frequency

f_m = channel bandwidth or in this case the baseband bandwidth

If this equation is applied to calculating the total speech-to-noise density ratio in a 1 Hz band at 500 Hz then

$$\left(\frac{P_{st}}{\Phi}\right) = \left(\frac{C}{\Phi}\right)\left(\frac{\overline{\Delta f}}{500}\right)^2 \qquad (22)$$

where $\overline{\Delta f}^2$ = mean square deviation caused by the total power in the speech spectrum.

Combining Equations 20 and 22 leads to

$$\left(\frac{P_{sm}}{\Phi}\right) = \left(\frac{C}{\Phi}\right)\left(\frac{\overline{\Delta f}}{500}\right)^2 \quad (.132 \times 10^{-2}) \tag{23}$$

If the test tone is now chosen such that the peak deviation it causes on the carrier is equal to the peak deviation caused by the speech power spectrum (full load test tone), one can then write:

$$\left(\frac{S}{N}\right)_{tt} = \frac{3}{2}\left(\frac{C}{\Phi}\right)\frac{K^2\,\overline{\Delta f}^2}{\left(f_m\right)^3} \tag{24}$$

where

K^2 = peak to rms factor for voice

$\frac{K^2\,\overline{\Delta f}^2}{2}$ = rms deviation by test tone

f_m = voice baseband

Combining 23 and 24

$$\left(\frac{S}{N}\right)_{tt} = \frac{3\,K^2}{2\,f_m^3}\left(\frac{P_{sm}}{\Phi}\right)_{500}\frac{(500)^2}{(.132 \times 10^{-2})} \tag{25}$$

Equation 25 relates output full load test tone-to-noise ratio at the highest frequency in the baseband (i.e., where the noise is greatest) to the mean speech power-to-noise density ratio at 500 Hz. Reference 16 provides the final relationship between AI and $\left(\frac{P_{sm}}{\Phi}\right)_{500}$ required to link the test tone-to-noise ratio to articulation index. This relationship is plotted in Figure 4-10a. From the plot a 24-db full load test tone-to-noise ratio is seen to result in an articulation index of 0.7. This AI in turn is equivalent to 95 percent intelligibility based on a 250 phonetically balanced word list (Reference 17).

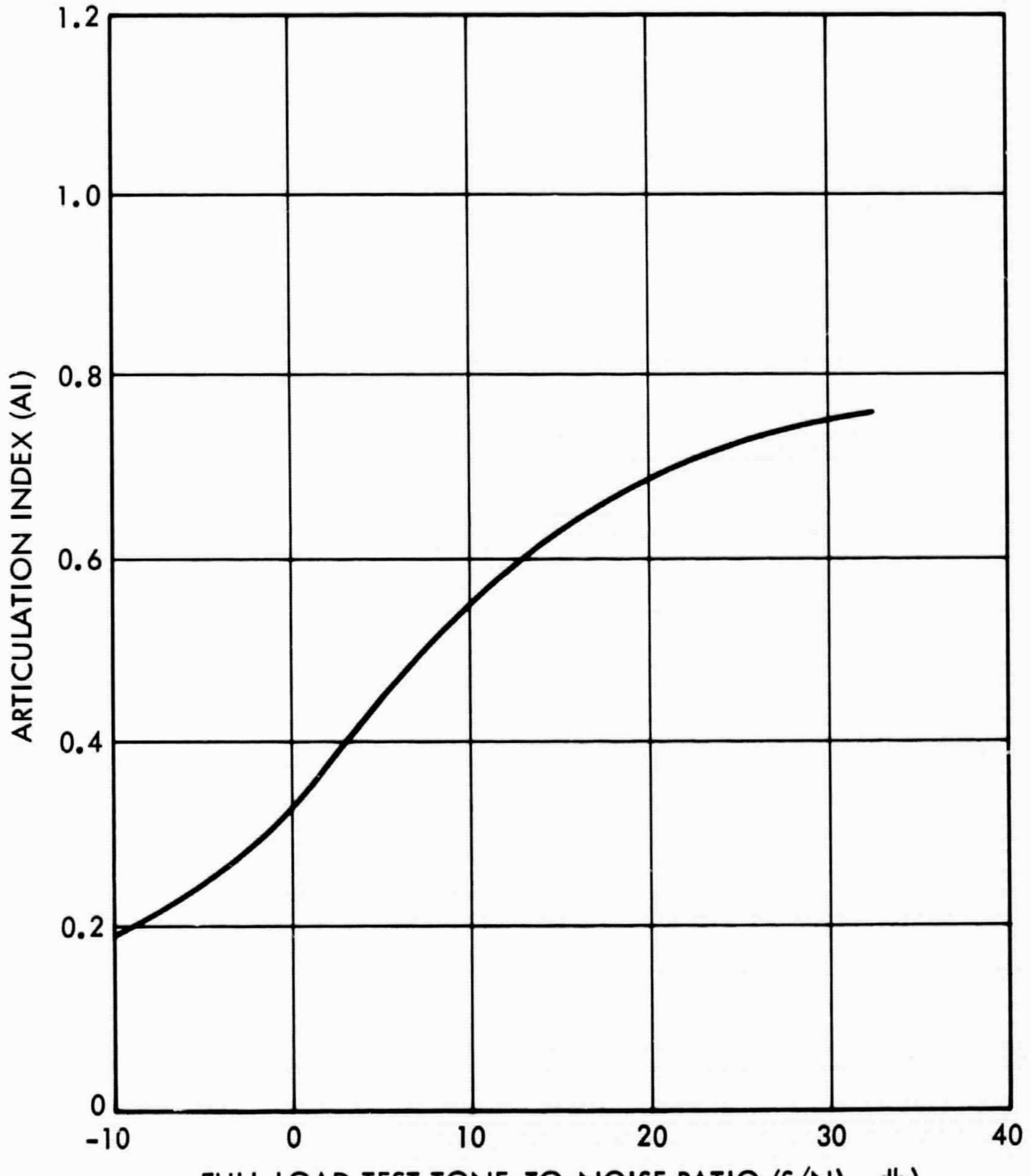


Figure 51. AI as a Function of Test Tone-to-Noise Ratio

4.5.3 Data

For data communications separate RF channels from voice will be used. Each channel will transmit a binary data stream at a rate of 1200 bps. This transmission speed has been selected for two reasons. First, the Radio Technical Commission for Aeronautics has selected a standard transmission speed of 1200 bps for aeronautical air-ground communications in the bands of 118 to 136 MHz and 225 to 400 MHz. Second, the communication load analysis shows that this speed is more than adequate to handle all expected data requirements for the aeronautical comsat service in the 1972 to 1975 time period. However, because of queuing problems and less than 100 percent utilization of such a channel, two data channels will be implemented. The first channel will be used to transmit autorep data, and the second one will be used to transmit company/weather messages as well as other routine messages.

Digital modulation techniques for the data channels can be divided into two categories, coherent and noncoherent systems. Coherent systems require a knowledge of the phase of the transmitted signal, while noncoherent systems operate on only the signal frequency or envelope. While coherent systems are more efficient, they are also more complex. Noncoherent techniques trade efficiency* for simplicity. An intermediate approach uses the the previous information signal as a phase reference for the following signal. This technique, known as a differentially coherent system, has been introduced to simplify the problem of obtaining the phase of the signal. Data systems are commonly evaluated in terms of their bit error rate of a particular ratio of signal energy per bit (E_b) to noise spectral density (N_o). Figure 52 shows the error rates for four of the most common binary modulation schemes—coherent PSK (CPSK), differentially coherent PSK (DPSK), coherent FSK (FSK), and noncoherent FSK (NCFSK).

*Coherent detection requires approximately 3 db less power than noncoherent detection.

The technique chosen for the ATC data application is DPSK. For small bit error probabilities (<0.001), the two forms of phase shift keying are within 1 db of each other in performance. The curves shown in Figure 52 assume optimum matched filter detection and the ratio E_b/N_o is equivalent to the signal-to-noise ratio in a bandwidth equal to the bit rate Assuming that nonoptimum filtering such as RLC or RC filters are used instead of the more difficult to mechanize matched filters, the performance will degrade about 1 to 2 db. Conservatively taking the upper value for the degradation, the required carrier (or subcarrier) signal power-to-noise density ratio for DPSK with a 10^{-4} bit error probability and 1200 bps transmission rate will be

$$\frac{C}{\Phi} = 9.5 + 2.0 + 10 \log 1200 = 42.3 \text{ db-Hz}$$

For noncoherent FSK

$$\frac{C}{\Phi} = 12.4 + 2.0 + 10 \log 1200 = 44.2 \text{ db-Hz}$$

The RF bandwidth for DPSK is about 3.6 kHz and about twice that for NCFSK.

A bit error probability of 10^{-4} has been established as the minimum acceptable (or threshold) bit error probability for the data transmission links. Since studies of message structure, acceptable message error rates, and coding for error detection and correction were not undertaken in this effort, this bit error probability was established somewhat arbitrarily. However, the following rationale does exist for this particular choice. A well-designed L-band satellite circuit should provide bit error probabilities of 10^{-4} to 10^{-5}. Error probabilities greater than 10^{-5} are probably difficult to achieve operationally. For example, typical wireline or HF data circuits for teletype are designed in general to provide bit error probabilities of 10^{-3}. Since parity check bits are provided in the data, single bit errors in a block of data will not go undetected. Therefore, a 10^{-4} bit error probability was felt to be adequate. However, subsequent studies of message structure and acceptable message errors may indicate that a bit error probability 10^{-5} is more desirable and/or that additional error coding is also desirable.

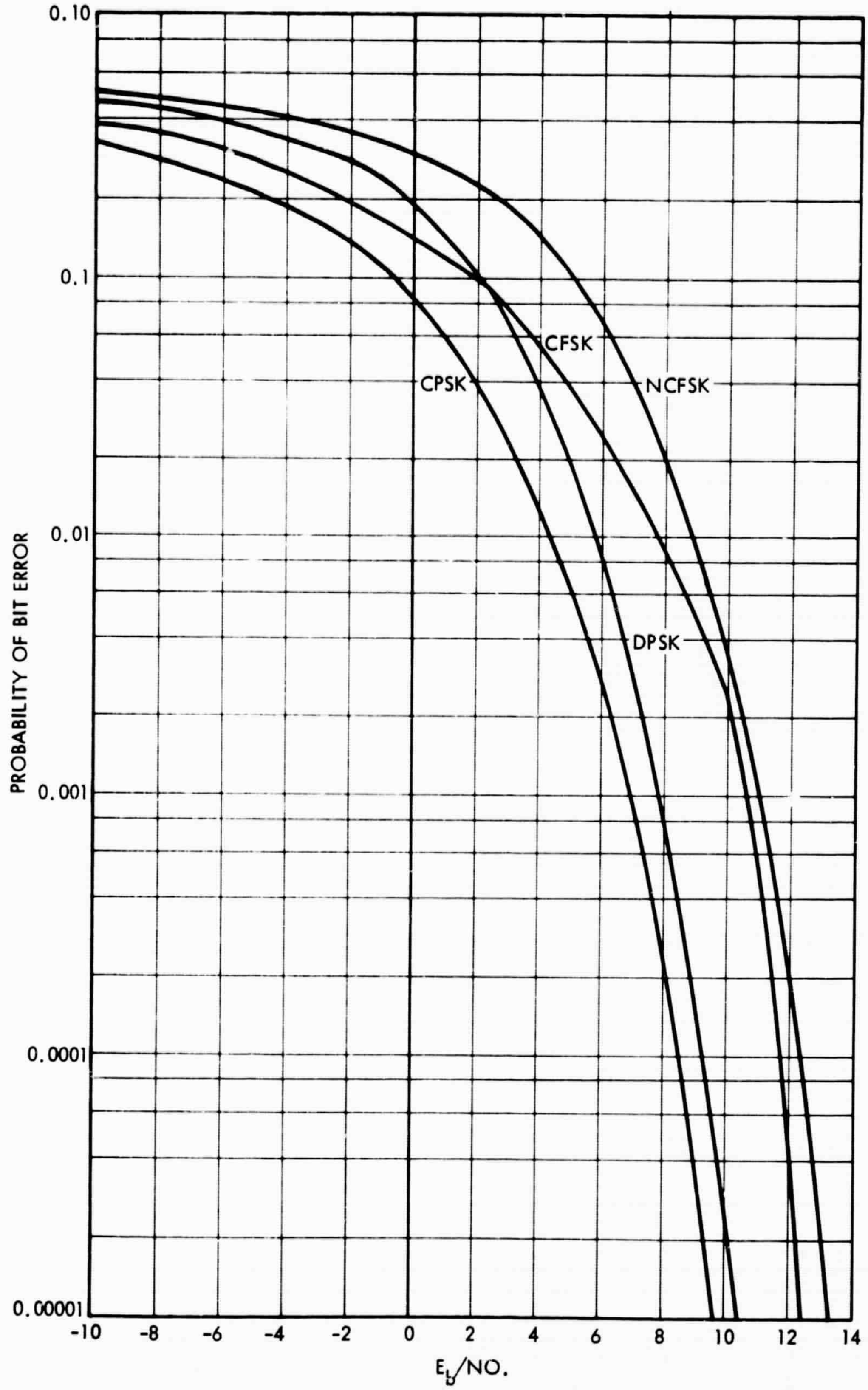


Figure 52. Error Rates for Data Modulation Techniques

4.5.4 Total Power Requirements for Voice and Data

4.5.4.1 Separate L-Band Carriers

The total required carrier-to-noise density ratio at the receiver is given by

$$\left(\frac{c}{\Phi}\right)_T = \left(\frac{c}{\Phi}\right)_A + \left(\frac{c}{\Phi}\right)_D \tag{26}$$

where

$\left(\frac{c}{\Phi}\right)_A$ = analog voice requirement

$\left(\frac{c}{\Phi}\right)_D$ = digital data requirement

This relationship will be used in the quantitative evaluation of total power requirements discussed in paragraph 4.5.4.3.

4.5.4.2 Unified Carrier Approach

In the case of sine or square wave subcarriers phase modulating the carrier, the following equations can be used to optimize modulation indices and calculate the required total carrier-to-noise density ratio. The power remaining in a carrier after phase modulation by N sinusoidal subcarriers and M square wave subcarriers is given by (Reference 18)

$$P_c = \prod_{i=1}^{M} J_o^2 (x_i) \prod_{j=1}^{M} \cos^2 (y_j) P_t \tag{27}$$

where

P_c = carrier power remaining

P_t = total power

$J_o (x)$ = zero-order Bessel function

x_i = phase deviation of the ith sine wave subcarrier

y_j = phase deviation of the jth square wave subcarrier

The recoverable power in the first order sideband of the nth sine wave subcarrier is given by

$$Psi_n = \frac{2J_1^2 (x_n)}{J_o^2 (x_n)} \prod_{i=1}^{N} J_o^2 (x_i) \prod_{j=1}^{M} \cos^2(y_j)\, P_t \qquad (28)$$

and the recoverable power in the mth square wave is given by

$$Psq_m = \frac{8}{\pi^2} \left[\frac{\sin^2 (y_m)}{\cos^2 (y_m)} \right] \prod_{i=1}^{N} J_o^2 (x_i) \prod_{j=1}^{M} \cos^2 (y_j)\, Pi \qquad (29)$$

These three equations have been solved under the following conditions:

- The carrier threshold was set equal to or better than any of the subcarrier thresholds
- The subcarrier thresholds were set equal so that as total received power decreases, all services fall below threshold simultaneously
- Under the above conditions as much useful power as possible must be obtained in the first order sidebands of each subcarrier.

The optimization procedure will only be briefly described. A relationship between Equations 28 and 29 is found using the c/Φ required for each subcarrier. This relationship links the modulation index of one subcarrier to the other. That pair of modulation indices that provides for a maximum power in the first order sidebands of the subcarriers is then chosen. Equation 27 places another requirement upon the remaining carrier power, but, in this case, the choice of modulation indices must be made on the basis of the subcarrier requirements since these services determine the maximum required $(c/\Phi)_T$.

4.5.4.3 Comparison of Approaches

Table 11 summarizes the total power requirements for the cases of phase-lock voice and either DPSK ro NCFSK. The results show that two separate carriers require less power total than the unified carrier approach and consequently two separate carriers for voice and data will be used.

Table 11. Optimization of Modulation Indices and Summary of Total Power Required

		Two L-band Carriers		One L-band Carrier Using 2 Sine Wave Subcarriers		One L-band Carrier Using 1 Square Wave and 1 Sine Wave Subcarrier	
		NCFSK	DPSK	NCFSK	DPSK	NCFSK	DPSK
C/Φ for analog voice only (db-Hz)		47.0	47.0	47.0	47.0	-	47.0
C/Φ for digital only (db-Hz)		44.2	42.3	44.2	42.3	-	42.3
Modulation Index Required (rad)	Analog voice	-	-	1.1	1.15	-	1.4
	Digital	-	-	0.86	0.75	-	0.67
Modulation loss for digital (db)		-	-	8.0	9.3	-	9.1
Modulation loss for analog (db)		-	-	5.2	4.6	-	4.4
C/Φ total required carrier-to-noise density (db-Hz)		48.8*	48.3*	52.2	51.6	-	51.4
Required satellite EIRP (dbw)		39.8	39.3	43.2	42.6	-	42.4

*Fictitious values, for comparative purposes.

4.6 CHANNEL ACCESS CONTROL

4.6.1 Multiple Access Techniques

The control of access to a multiple access satellite repeater is a key consideration in any communication system design. This is, of course, intimately related to the type of modulation as well as the form of multiple access used. Spread-spectrum multiple access (SSMA) simplifies the control problem by easing the conditions under which simultaneous access of all users can be obtained. Two other techniques, frequency division multiple access (FDMA) and time division multiple access (TDMA), require more coordination and control of subscribers in the operational system. To minimize the equipment complexity and simplify the communication procedures aboard the aircraft, FDMA has been selected as the multiple access technique. Since present HF and VHF channel utilization makes use of this approach, this technique is readily compatible with the existing ATC doctrine. Four methods of access can be identified for possible application with this access technique:

1) Random or uncontrolled
2) Monitored
3) Scheduled
4) Controlled.

4.6.1.1 Random Access

To use the random method of access, the probability of selecting an idle channel must be large (e.g., in excess of 98 percent). No control is required nor is the potential user required to monitor channel status. Each user would transmit messages randomly without any indication that the channel selected was free. An acknowledgement from the addressee would indicate to the sender that the message has been received. Failure to receive an acknowledgement within a predetermined time would result in a retransmission. As long as the probability of selecting an idle channel remained high enough, the number of retransmissions would be small. Although this access technique requires no control and little administrative traffic, it is less efficient than those discussed below and is susceptible to "clogging" if a number of conflicts occur and immediate retransmissions are attempted by all parties.

The random access technique seems particularly well suited for application with a spread spectrum multiple-access system. Since all potential users have simultaneous access to the satellite repeater, there is no need to allocate channels. The only control required is to limit the number of active users to ensure sufficient power is available to all. Also, SSMA degrades gracefully, i.e., any overload decreases only slightly the power available to all users. Thus, if the system is sized for a normal peak and a sudden overload condition occurs, the system can easily absorb the traffic increase without materially affecting the other active users. Should this overload increase to the point where the power level of all the active users drops below threshold, then all channels will be lost. To guard against such an eventuality, a simplified control channel can be added. This controlled random access operates as follows: A selected ground station constantly monitors the message traffic. When the traffic builds to a designated peak, the ground station continually transmits a "busy" message over the control channel. All users, when not actively communicating, will monitor this channel. Therefore, a user need only know that the satellite is not overloaded before beginning transmission. Should the satellite be overloaded, the user must wait until the repeater becomes available, i.e., until the busy message ceases.

The control channel, therefore, is utilized only during peak traffic periods and then only as long as it is required. Using this SSMA technique, the results of the communication load analysis are directly applicable. The busy time, i.e., all channels occupied, can be interpreted as the amount of time the satellite is overloaded.

4.6.1.2 Monitored Channel Access

The monitoring method improves efficiency by requiring some type of listening by the sender to determine channel status. Message transmission occurs only when a free channel is available. The pilot either searches for an idle channel or waits for an assigned channel to become idle. The form of the monitoring can vary from listening to the channels to automatic energy detection. Both techniques were considered, and although the automatic energy detection and channel switching device appeared attractive, the communications load analysis indicates that it is not required from that standpoint. However, as suggested by L. M. Keane a "busy signal" may be used to conserve satellite power.

4.6.1.3 Scheduled Access

Access by scheduling, although the least flexible, is attractive because it is efficient. In this case, each user is assigned a channel and specific times at which it should be used. Messages would be transmitted only at those specified times. Assignments may be made either before a flight or continuously during a flight. One of more channels would be allocated for administrative use, e.g., for assigning schedules to subscribers first entering the system, for requests for different transmission times, and for nonroutine or otherwise unscheduled traffic. Because of the ready availability of a good clock which is associated with the NAVSTAR system, the time slot technique was at first favored for the Autorep surveillance data reporting, but, as indicated in paragraph 4.6.3, roll call controlled access was selected for the Autorep function.

4.6.1.4 Controlled Access

Controlled access provides the greatest efficiency and the most flexibility, although at a cost of procedural complexity and small access delay. In this method, the control channels are reserved for administrative control, e.g., message requests, assignments, etc. Each user would contact a central traffic controller via this channel each time it wishes to transmit. The controller would then assign it one of the idle communications channels. By limiting the number of potential users allotted to each control channel and restricting traffic to short duration administrative messages, the channel duty cycle can be kept low. This ensures that any user will have a high probability of finding the control channel idle when wishing to request a communications channel. An additional feature of this scheme is that the control channel can serve as a "party line" for all users. Thus, any time a user is not transmitting, it need only to guard or monitor this control channel to determine if any other user wishes to contact it. Furthermore, the receiver at each user can be modified to accept only messages addressed to it over this control channel. This provides a simple and reliable means for the ATC station to selectively contact any (or all) aircraft. One final advantage inherent in this technique is that it easily allows different forms of queue discipline, since this discipline is essentially established by the procedures and equipment available to the traffic controller. Because the controller has the current status of all channels, an idle one can be located readily. In addition, a priority system can be easily introduced, if required, and the queue discipline can even be made time-varying to better match the fluctuating traffic pattern. The operational flexibility of this technique is readily apparent, and the mechanization is straighforward, requiring little additional equipment. All gains are made at the expense of procedural complexity and a somewhat greater delay in message delivery.

4.6.2 Voice Communications

The navigation/traffic control satellite system voice communications will be made up of twelve half-duplex channels. The voice channels will be designed such that the uplink to the satellite from both users and ground stations will be at frequencies in the 1640 to 1660 MHz range, and the downlink from the satellite to both users and ground stations will be at frequencies in the 1540 to 1560 MHz range. The twelfth voice channel, identical to the other eleven in design, will be identified as the emergency or guard channel. Each user will have an additional receiver set tuned to the emergency channel downlink frequency. The purpose of the arrangement is that it is desirable that users be able to transmit and receive on, say, channel 2, but at the same time, be able to guard the emergency channel. Therefore, in order that users be able to simultaneously hear transmissions of both channel 2 and emergency channel, two receivers are required. In the event that the user needs to transmit on emergency, the operator would simply move his selector switch from channel 2 to the emergency position. Access to any of the voice channels is obtained by monitoring the channels for their busy status. The pilot can either search for an idle channel or wait for an assigned one to become idle (or some combination in the event that some but not all channels are available to him).

A simplified ground-satellite-aircraft voice link is shown in Figure 53a. Note that the satellite-to-ground and satellite-to-aircraft downlink frequencies are identical. The primary reason for this mechanization is so that aircraft flight crews can determine whether or not a voice channel is in use simply by listening for voice transmissions, as done on VHF/UHF aircraft voice links today. Significant savings in satellite power could be obtained by placing the satellite-to-ground and satellite-to-aircraft links on different frequencies, and allowing the satellite to transmit much less power on the satellite-to-ground link (say, 1 watt as opposed to 40 watts). This later option was not chosen because it would not only eliminate the voice monitoring capability but would also render the system incapable of providing aircraft-to-aircraft voice links for over-the-horizon long-distance communications. Furthermore, this technique would also require additional assigned frequencies. The idea is not without merit, however. In addition to the savings of satellite ERP, further analyses might show that it is, in fact, desirable to have satellite-to-ground communications at frequencies which might be in use by aircraft but where interference is avoided simply by having the satellite broadcast at that frequency with insufficient radiated power to be picked up by aircraft with low-gain receiver antennas.

Also indicated in the figure is a ship. It should be noted that the user antenna onboard the average ship could very well have a much higher gain than the aircraft antenna—say, 10 db. Thus, satellite-to-ship downlinks could take advantage of this fact allowing lower satellite radiated power at those frequencies. Certainly in a preliminary design phase wherein specific frequencies in a firm frequency plan were allocated for marine use, additional channel capacity or conversely, smaller satellites, or some other optimization or design could take place by taking advantage of this fact. In this study, however, TRW has not been able to go into marine requirements to the extent required to determine whether or not full time assignment of frequencies to marine users is really the best option. It appears that assignment of aviation voice channels to marine craft during off-peak hours might be the best utilization of this satellite communications capability and this is the study recommendation. In this case the satellite could only take advantage of the higher gain shipboard antennas if an adjustable power setting were available on the satellite which could be commanded from the ground. It is by no means clear that the increased complexity and therefore reduced reliability associated with this approach would be the right design approach.

4.6.3 Data Communications

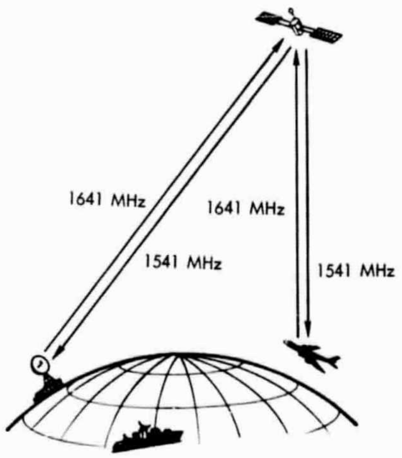
4.6.3.1 General

The Navigation/Traffic Control Satellite System is configured to handle three types of data messages as follows:

- The Autorep message—transmitted from aircraft-to-ground on a roll call basis.
- The weather message—from ground-to-aircraft at ground time convenience, and from aircraft-to-ground on a ground permission basis.
- The company message—from ground-to-aircraft at ground time convenience, and from aircraft-to-ground on a ground permission basis.

Figure 53 illustrates the data links between users and a ground station. All the links operate at 1200 bits per second. As illustrated the Autorep and roll call* links are on separate channels. The Company/weather link is a half duplex channel with users' access to this channel controlled by ground stations, who grant permission to users requesting the channel (see Paragraph 4.6.3.3). User requests are transmitted on the Autorep channel; and ground station permission to users, as well as acknowledgement of received messages, are transmitted on the roll call channel.

*If time slots are implemented this channel can be eliminated.



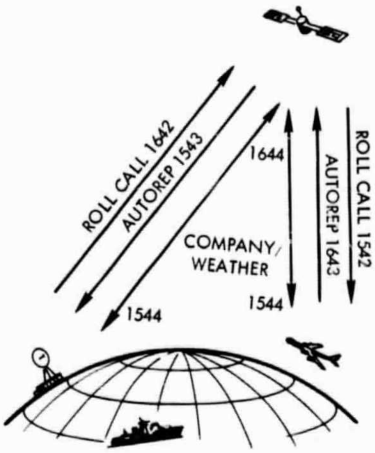


Figure 53a. Typical Voice Communications Link

Figure 53b. Typical Data Communications Links

The Autorep message serves as a carrier for certain short coded messages which ride piggyback. The Autorep messages are transmitted frequently enough so that this does not present a significant delay problem and the technique results in a higher utilization efficiency in the communication channels. The Autorep message format and content is illustrated in Figure 54. With the exception of the altimeter data and the data contained in the Autorep piggyback word, all of the data in the Autorep message is extracted from the output of the NAVSTAR preprocessor.

Access to the Autorep channel by users can be solved by two different approaches and by a combination of these two approaches. In the first approach, users transmit their Autorep data only upon receipt of ground station requests (the roll call method). The ground station can address a group of users in any sequence or frequency of contact desired. In the second approach each user is assigned a time slot in which to transmit his Autorep data. The time information, supplied as part of the navigation signal transmissions, can be used to aid in the time synchronization required between users. The assignments of time slots to users can be made by the ground station. Finally, a combination of these two approaches can be used. Users would ordinarily broadcast in their assigned time slots; however, the ground station could override this system by sending appropriate instructions to all users. Instructions could make available more time slots to certain users and fewer time slots to other users or could change the mode of operation from time slots to ground station roll call.

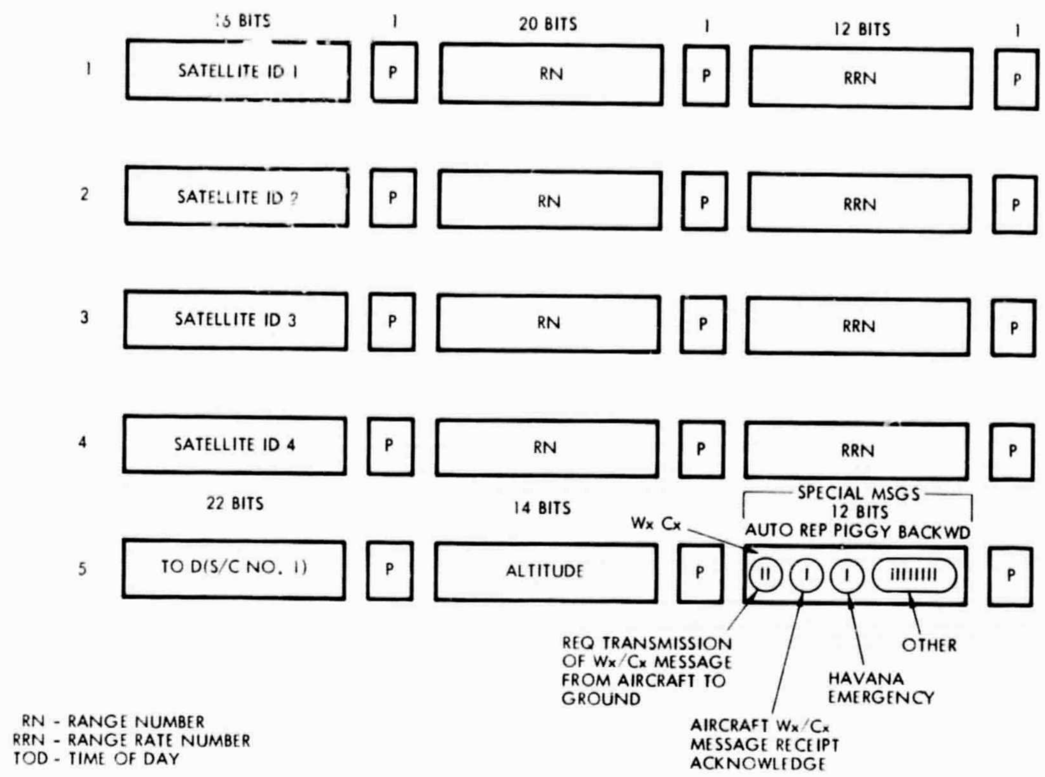


Figure 54. Autorep Message Format and Content

Of the two basic approaches, the first appears to be the most attractive since it allows for more flexible operation of the traffic control network. However, time slots have the advantage of eliminating ground station transmissions for the Autorep function. The disadvantage of the time slot approach is that synchronization required between users. In order to obtain maximum utilization of the autorep channel, the synchronization accuracy should be good. All users must obtain their timing information from one of the satellites in the network. Since a satellite does not broadcast the time information continuously, users must have an accurate clock to provide timing information between the satellite transmissions and a clock which is capable of being resynchronized at each satellite transmission. It is felt at the present time that the roll call method will result in the simplest user equipment and is therefore the recommended approach to provide access to the Autorep channel by users. Further study may indicate that the time slot approach is actually the preferred method, but for the present the roll call approach will be designed into the navigation/traffic control satellite system.

4.6.3.2 Autorep Sequence

The Autorep sequence is initiated by command from a ground station. The command message is received, demodulated, and examined for correct address (each airplane has a unique address). The main body of the message is a code which is interpreted by the decoder as an order to transmit the Autorep message. The data in the Autorep buffer is sent to the message formatter and output control which combines the data from the Autorep buffer with the address code of the airplane and sends the message to the ground via the modulator and transmitter. Data from the NAVSTAR preprocessor is selected and stored in the Autorep buffer. The Autorep buffer is updated repetitively but is locked out during message transmission to avoid partial overwriting of data during transmission. The Autorep message itself is, in effect, an acknowledgement of the ground station message which orders transmission of the Autorep message. Therefore, no further acknowledgements are required; the Autorep buffer terminates its cycle upon completion of the transmission and updating of data commences again.

Use of the Autorep special message word eliminates several special acknowledge messages going back and forth between the airplane and the ground—it eliminates message overhead, namely, the start-up and turn-off of conversations. If an aircraft were sent two messages without an intervening acknowlegement, we have an ambiguity, i.e., the people on the ground are not completely sure whether the aircraft received one message or the other, or both, but they know that he received at least one. They might presume at least that his equipment is in order. Trade-offs might indicate use of more bits if it is desired to actually show how many messages had been acknowledged. The ground station may send a message of general interest to all aircraft in the area. The message would consist of a universal address code followed by the main text of the message. The aircraft decoder unit, therefore, must be wired to recognize the universal address code as well as the specific aircraft address, transmit orders, and receipt acknowledge codes. Aircraft receiving the message of general interest would acknowledge receipt in the usual fashion.

4.6.3.3 Company/Weather Message Sequence From Aircraft to Ground

These messages are assembled on the alphanumeric display and keyboard machine. The message is constructed a line at a time, and as the lines are constructed they appear on the CRT display (the operator, pilot, or stewardess does that with the keyboard). As the lines are formed they are stored in the message buffer. Mistakes are corrected by means of the "Line Erase" button which permits the last line of the message to be retyped. Having constructed a message which consists of a maximum number of 10 lines, the complete message is stored in the message buffer. It is now possible to take one action which will result in transmitting this message to the ground without any further action required of the operator. This process is initiated and latched. The "Message Actuate" button causes a tag or code bit to be inserted into the next auto-rep message which will be sent to the ground. The ground station will then recognize this special tag as a request for permission to transmit a message. The tag also identifies the message as weather or company. The ground station resolves the message priority problem and calls for transmission of company and weather messages in proper order. When it is permissible to transmit the message, the ground station activates the process by itself without any further requirements on aircraft personnel.

The ground station will send a message to the aircraft which will be received and demodulated and address decoded as usual. This message will consist of a special code which is a transmit order. The transmit order will be decoded in the decoder unit and sent to the message formatter and output control. This unit will cause the message to be read out of the message buffer and transmitted to the ground. The message is read out of the message buffer through the IO channel to the message formatter and output control where it is combined with the address code which identifies it as coming from this particular airplane. The combined message is then transmitted to the ground. The ground station, having received the message that originated in the airplane, now acknowledges receipt of that message. This is done by transmitting a very short acknowledge message which is demodulated, address checked, and decoded in the aircraft. Receipt of the ground receipt acknowledgement now comes back to the message entry CRT display device and extinguishes the

"Message In" light which completes the cycle. The pilot knows the message has been received by the ground. This was accomplished by pushing only one button—the "Message Actuate" button. It might take as long as several minutes before the light goes out in heavy traffic, but considering the priority of the messages, we feel that it is acceptable.

4.6.3.4 Company/Weather Message Sequence From Ground to Aircraft

These messages are received, demodulated, address decoded, and routed into the message buffer. They are stored temporarily in the message buffer and then printed on the hard copy printer. The message which is printed on the hard copy printer will have an end code, and upon receipt of this, the operator will initiate an aircraft receipt acknowledgement by pushing a button on top of the hard copy printer. This generates a very short message code which is transmitted to the ground piggyback via the autorep message.

4.7 POWER BUDGETS

4.7.1 General

The results of all the previous investigations and analyses are integrated in the power budget. These budgets can then be used to determine the satellite RF power required to support both a voice channel and a 1200-bps data channel. This power requirement is critical to the system design since it determines the dc power requirements that the satellite must satisfy or specifies the number of carriers that the transponder can accommodate given the available satellite dc power.

4.7.2 Satellite-to-Aircraft Downlink Power Budget

The critical link in this system is the satellite-to-aircraft downlink. Power budgets for voice have been developed at the three frequencies of interest, i.e., VHF, L-band, and C-band. The budgets are based upon the hardware technology that is expected to be available in 1975. The results show the attractiveness of L-band for the voice transmissions. C-band requires a high-gain aircraft antenna to offset the increased space loss over L-band. At VHF a larger satellite-radiated power is required to offset the lower antenna gain achievable on the satellite and the increased propagation losses. However, it should be said that at VHF higher transmitter dc to RF power efficiency is available and the aircraft antenna requirements are slightly less complicated (0 db gain versus 4 db gain at L-band), i. e., VHF, L-band, and C-band are presented in Table 12.

The technique used in producing these budgets was to calculate the nominal (or average) values of all variables (both stochastic and deterministic) for an aircraft possessing a 20 degree elevation angle to the satellite. The selection of a 20 degree elevation angle to the satellite is a conservative estimate for most of the North Atlantic corridor which is the area of primary interest. To these predictions was added a 6 db margin requirement. The C/N_o for the voice channel which represents the most demanding case was calculated to provide a signal-to-noise ratio of 24 db in a 3 kHz baseband. A moderate clipping level of 6.8 db was also assumed. The CCIR recommendations for space communications were used as the basis for these characteristics. These recommendations were predicted on providing an acceptable voice channel with a moderate sacrifice in speech quality that is considerably more reliable than conventional mobile communication. This may be unduly strict for routine air-to-ground communications, but it does provide a valuable upper bound.

4.7.3 Band Power Budgets

Power budgets for all four satellite links have been developed for the carrier frequency chosen, L-band. These budgets for both the voice and data channels are shown in Table 13. A voice channel requires 40 watts of satellite radiated power and a data channel 20 watts. However, since data has a slightly larger margin it may be desirable to put some additional power in the voice channel at the expense of the data channel. Increasing the voice channel power to 40 watts while reducing the data channel to 12 watts would provide the same margins for both signals. The satellite-transmitted power to the ground station is the same as to the aircraft even though better than 20 db margin exists at the ground station. This is done so all aircraft can monitor the transmitting aircraft's messages to the ground station in order to determine channel status and to permit aircraft-to-aircraft transmissions via the satellite.

The aircraft transmitter power required is 300 watts average for both voice and data. If both are transmitted simultaneously either two 300-watt transmitters or a single transmitter capable of handling both carriers simultaneously would be required. In the latter case, the

Table 12. Comparison of Satellite-to-Aircraft Downlinks for Voice (Satellite Power Requirements to Obtain a 6-db Margin)

	VHF	L-Band	C-Band
Satellite RF power per channel (watts)	79.0	43.5	43.5
(dbw)	19.0	16.4	16.4
Satellite circuit losses (db)	-1.0	-1.0	-1.0
Satellite antenna gain (at beam edge) (db)	14.0	23.0	23.0
SATELLITE EIRP PER CHANNEL (dbw)	32.0	38.4	38.4
Space loss	-167.2	-188.4	-199.0
Atmospheric and ionospheric losses	-3.0	0.0	0.0
Multipath loss	-5.0	-1.0	-1.0
Polarization loss	-1.0	-1.0	-1.0
TOTAL LOSSES (db)	176.0	-190.4	-201.0
Aircraft antenna gain (at beam edge) (db)	0.0	4.0	15.2*
Aircraft receiver losses (db)	-1.5	-1.5	-1.5
AIRCRAFT RECEIVED CARRIER POWER (dbw)	-145.7	-149.5	-148.9
Aircraft receiver noise figure (db)	2.0	3.0	3.5
Aircraft receiver noise temperature (°K)	170	290	360
Aircraft antenna noise temperature (°K)	1005	50	35
Aircraft system noise temperature (°K)	965	410	470
Aircraft system nose temperature (db)	29.9	26.1	26.7
Boltzman's constant	-228.6	-228.6	-228.6
AIRCRAFT RECEIVER NOISE DENSITY (dbw/Hz)	-198.7	-202.5	-201.9
Received C/N_o (db-Hz)	53.0	53.0	53.0
Margin (db)**	+6.0	+6.0	+6.0

*Required for same satellite radiated power as L-band.

**Based on 47 db-Hz required of C/N_o for a voice channel.

Table 13. L-Band Power Budgets

	Ground-to-Satellite Uplink (1650)	Satellite-to-Aircraft Downlink (1550)		Aircraft-to-Satellite Uplink (1650)	Satellite-to-Ground (1550)	
		Voice	Data*		Voice	Data*
Transmitter power (dbw)	20.0	16.0	13.0	24.8	16.0	13.0
Power loss due to uplink noise (db)	-	0.0		-	-1.2	
Circuit losses (db)	-1.5	-1.0		-1.5	-1.0	
Antenna gain (db)	25.0	23.0		4.0	23.0	
EIRP	43.5	38.0	35.0	27.3	36.8	33.8
Space loss	-189.0	-188.4		-189.0	-188.4	
Multipath loss	0	-1.0		-1.0	0	
Polarization loss	-0.5	-1.0		-1.0	-0.5	
TOTAL LOSSES (db)	-189.5	-190.4		-191.0	-188.9	
Antenna gain	23.0	4.0		23.0	25.0	
Circuit losses	-1.0	-1.5		-1.0	-1.5	
RECEIVED CARRIER POWER (dbw)	-124.0	-149.9	-152.9	-141.7	-128.6	-131.8
Receiver noise figure (db)	5.0	3.0		5.0	4.0	
Receiver noise temperature (°K)	630	290		620	440	
Antenna noise temperature (°K)	290	50		290	290	
System noise temperature (°K)	920	410		920	730	
System noise temperature (db)	29.6	26.1		29.6	28.6	
Boltzman's constant	228.6	228.6		228.6	228.6	
RECEIVER NOISE DENSITY (dbw/Hz)	-199.0	-202.5		-199.0	-200.0	
Received C/N_o (db/Hz)	-	52.6	49.6	-	71.4	68.4
Required C/N (db/Hz)	-	47.0	42.3	-	47.0	42.3
Receiver noise bandwidth (db)	47.0	-	-	47.0	-	-
Receiver noise power (dbw)	-152.0	-	-	152.0	-	-
Received S/N	28.0	-	-	10.3	-	-
Required signal-to-noise ratio (db)	20.0	-	-	5.0	-	-
Margin	8.0	5.6	7.3	5.3	24.4	26.1

*A blank space signifies the value corresponds to the value in the voice column.

transmitter must be capable of handling 1200 watts peak power since both voice and data carriers will add in-phase at times.

The experimental R&D system may require a higher satellite radiated power for voice and data since the power budgets in Table 13 reflect expected 1975 technology with regard to the 3.0 db receiver noise figure. Higher noise figures (4 to 5 db) can be expected for the 1972 date of the R&D satellite. For this reason, 60 watts of radiated power for a voice channel will be made available for the R&D satellite.

4.8 COVERAGE PATTERNS

4.8.1 General

In an effort to reduce the satellite power requirements necessary to support an analog voice channel when the aircraft has only a low-gain (3 to 4 db) antenna, the possibility of using higher gain, elliptical beam, or steerable satellite antennas was investigated. The case given primary interest was the North Atlantic Corridor although some attention was provided in the Pacific. Two orbital configurations were analyzed: the equatorial synchronous (stationary) and the inclined circular synchronous. Coverage plots were generated for a variety of antenna beamwidths (i.e., antenna gains) under the basic constraint that the beamwidth should be sufficient to illuminate all of the desired area.

4.8.2 North Atlantic Ocean Area (NAOA)

The primary area of interest is the air corridor linking North America to the major north European cities (London, Paris, etc.). This corridor lies between 40 and 60 degrees north latitude and 0 to 70 degrees west longitude (Figure 55). For the stationary orbits two beam configurations were examined, circular and elliptical. The elliptical beam is more efficient since it can be tailored to an essentially rectangular requirement with little energy diverted to areas outside this corridor. As indicated in the table of Figure 55, however, the antenna dimensions for the elliptical beam are somewhat larger and, in fact, were not compatible with the selected shroud design and required more sophisticated folding techniques. Therefore, circular beam antennas are used in the navigation/traffic control satellite design. Elliptical beam coverage, however, clearly merits further consideration and in the preliminary design phase might well turn out to be a preferable approach. The choice between the two is not a major design factor that would affect system feasibility.

The coverage patterns for both these antenna configurations are shown in Figure 55 for various ellipticities. The beams for each of these patterns are centered at different points as shown on the diagram. The maximum antenna gain associated with each of the beamwidths is also given in Figure 55. It should be pointed out that these are the patterns generated for a minimum elevation angle of 20 degrees (angle from the aircraft to the satellite). Figure 56 shows how the coverage changes for different elevation angles. The differences due to various elevation angles have been shown for two cases, the high antenna and an earth-coverage antenna, both pointed toward the center of the North Atlantic. It can easily be seen that most aircraft view the satellite from an angle of 25 to 30 degrees. Thus the 20 degree elevation angle used in the previous figure represents a lower bound.

For the inclined circular synchronous orbit, the coverage pattern changes as the satellite changes position. For this case, the ground track of the satellite traces out a figure-eight design with the crossing point of the eight centered at the nominal longitude of the satellite at the equator. The nortnern (or southern) furthermost point of the figure-eight design is determined by the inclination of the orbit. Two different inclinations have been examined: 16 and 30 degrees. These represent the bounds within which the operational system will probably operate. Figure 57 depicts the coverage pattern for a high-gain antenna in a 30 degree inclined orbit while Figure 58 gives the patterns for an earth-coverage antenna. It has been assumed that in both cases the antenna is constantly steered so that coverage is obtained in the desired geographical area. In both of these figures the aiming point is assumed to be continuously moving from point A to point B as the satellite increases its latitude. The three different patterns show the coverage as the satellite moves from its furthermost southern point to its northernmost point. Figures 59 and 60 give the same coverage patterns for a satellite in an 18 degree inclined circular synchronous orbit. As before, the minimum elevation angle in all four figures is 20 degrees.

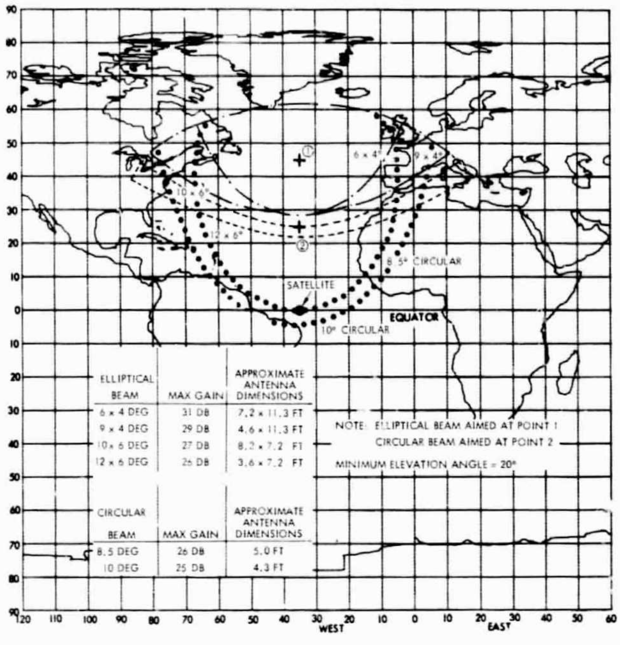


Figure 55. High-Gain Antenna Coverage Patterns

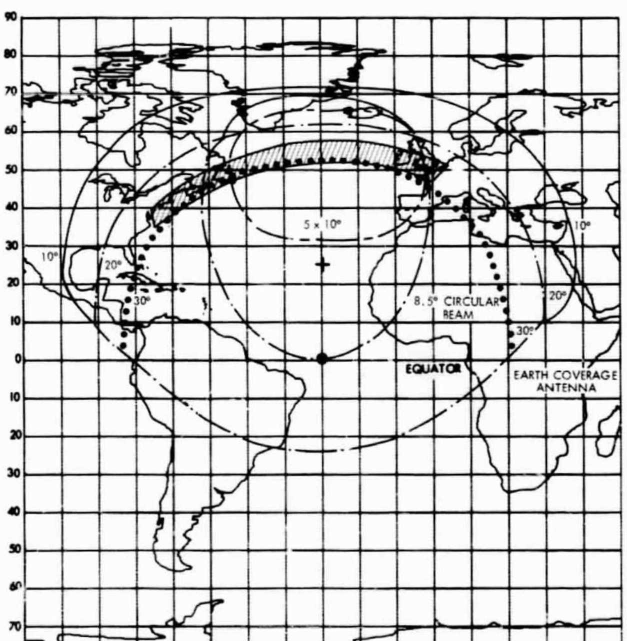


Figure 56. Antenna Coverage Patterns for Various Elevation Angles

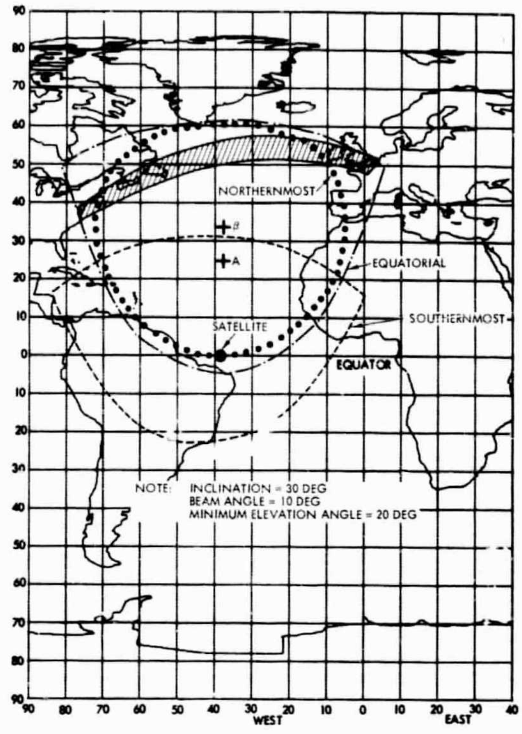


Figure 57. Coverage Patterns for a High-Gain Satellite on an Inclined Synchronous Satellite

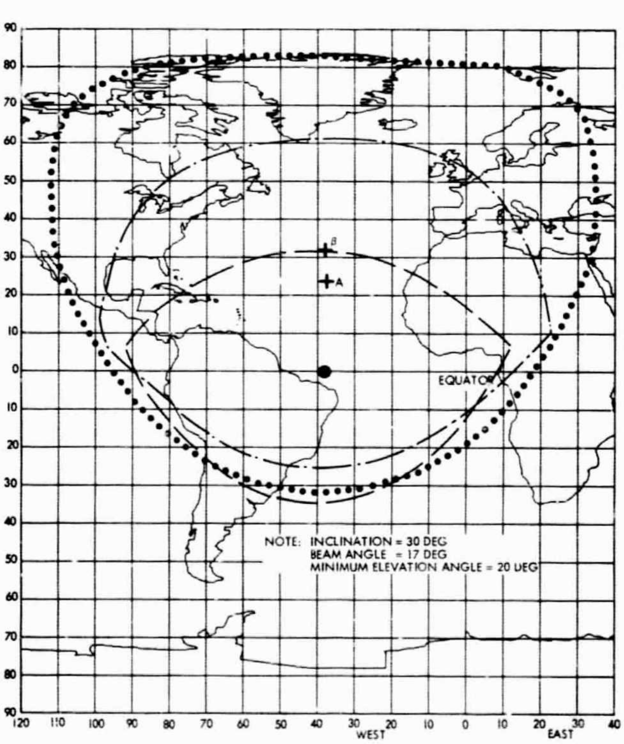


Figure 58. Coverage Patterns for an Earth-Coverage Antenna on an Inclined Synchronous Satellite

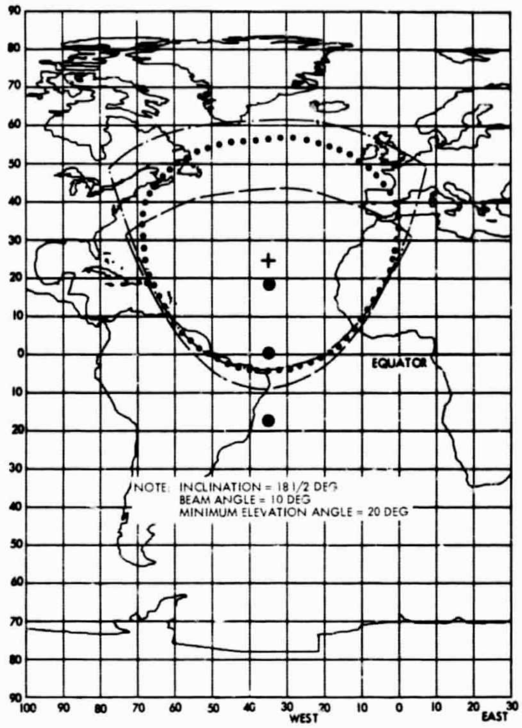


Figure 59. Coverage Patterns for a High-Gain Satellite Antenna on an Inclined Synchronous Satellite

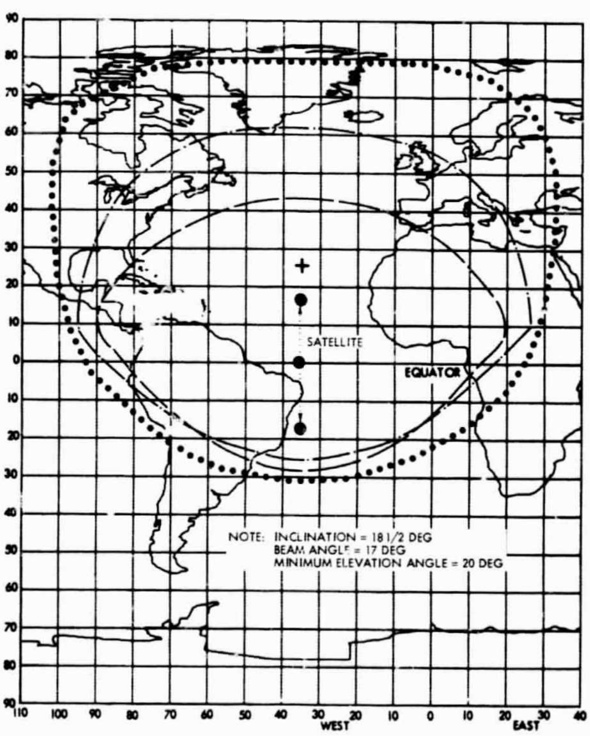


Figure 60. Coverage Patterns for an Earth-Coverage Antenna on an Inclined Synchronous Satellite

4.8.3 Pacific Ocean Area

The Pacific coverage patterns for both earth-coverage antenna and a high-gain (maximum gain = 31 db) antenna are shown in Figure 61. Since the air corridors (Reference 19) are more dispersed in the Pacific than in the NAOA, the utility of high-gain satellite antennas is in question. As can be seen from the above figure, there may be some use for this type of antenna is serving mobiles between Hawaii and the mainland of North America. Once again, the coverage for the three most interesting satellite positions—nominal, northernmost and southernmost—have been plotted.

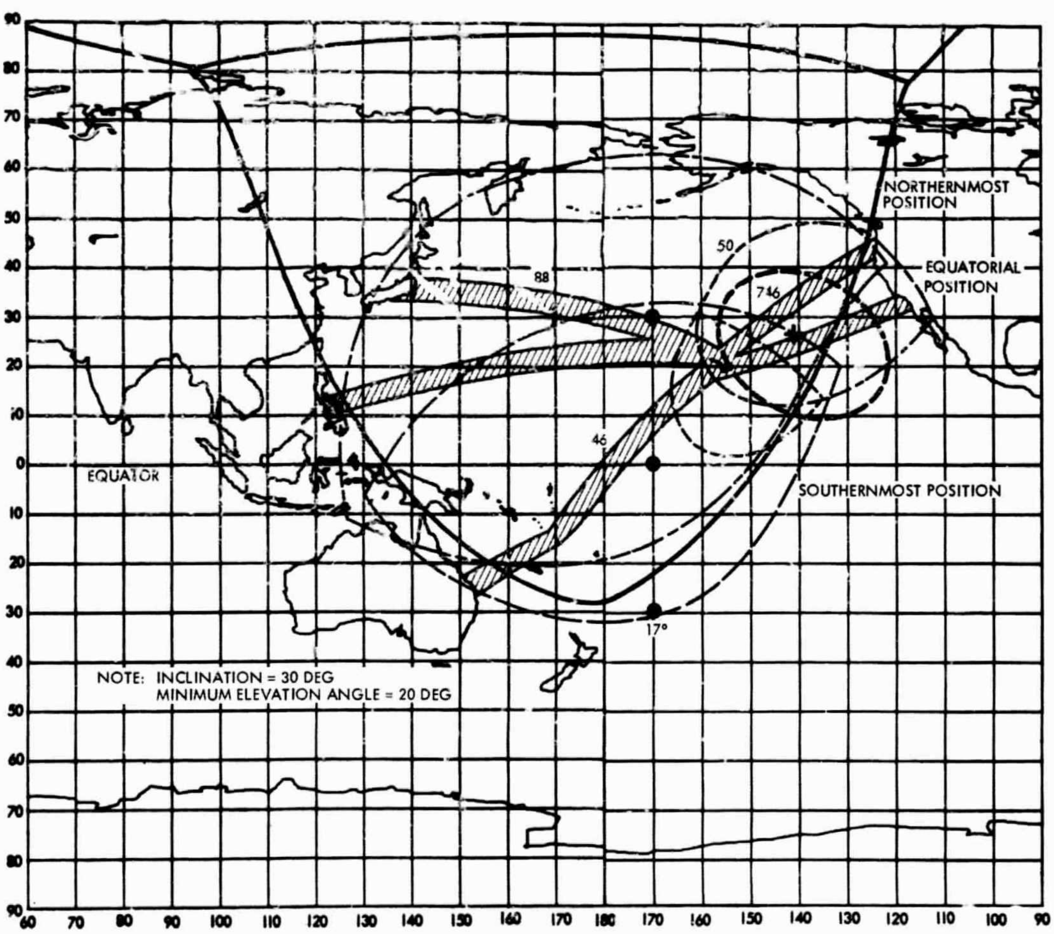


Figure 61. Pacific Coverage Patterns for an Inclined Synchronous Satellite

4.8.4 Pseudo-Stationary Satellite Constellation Coverage

One of the most attractive NTCS constellations which is developed in Section 4 of Volume III is a combination synchronous, circular, equatorial and synchronous elliptical inclined set of orbits. Figure 62 shows the communications coverage provided in North and Central America, in North and mid-Atlantic Ocean, Western Europe, North Africa and Asia Minor by four synchronous equatorial satellites stationed at 13°East, 15°West, 56°West, and 94°West Longitudes. The coverage patterns shown are provided by an 8° (23 db beam edge) circular beam tilted northward such that the southernmost coverage is provided at the sub-satellite point. The northernmost coverage as indicated in the figure will be somewhere between 60 and 70°. The area above the solid coverage lines near 60° and below the dotted coverage lines near 70° represents that area which is illuminated by the 8° beam but wherein the user sees the satellite at an elevation angle between 10 and 20°. Further analyses and test work would be required to indicate the quality of performance attainable in this area. The most like problem will be garbling of the voice communications due to multipath effects.

Figure 63 shows the coverage obtained at two points in time by satellites placed in synchronous orbits with an inclination of 52.5° in an eccentricity of 0.35 with the apogee occurring when the satellite is at its northernmost position in the orbit. The 8° circular beam antennas for these satellites are pointed straight down. Comparison of Figures 63 and 62 shows that the inclined orbit satellites provide, at the 6- and 18-hour points, only redundant coverage (i.e., the same as the equatorial satellites), but that the satellite in the zero hour point does provide substantial additional near-polar communications coverage. A brief examination of airline schedules for polar flights between the West Coast of the United States and Northern Europe indicates that a good "zero hour" for these satellites would be in the early afternoon Greenwich time. In this case, however, there is still some sacrifice in coverage for the eastbound flights when they are still over Canada and for the westbound flights just after takeoff. If further study shows that the requirement for coverage for these polar flights is great enough, higher inclination and eccentricities can be used.

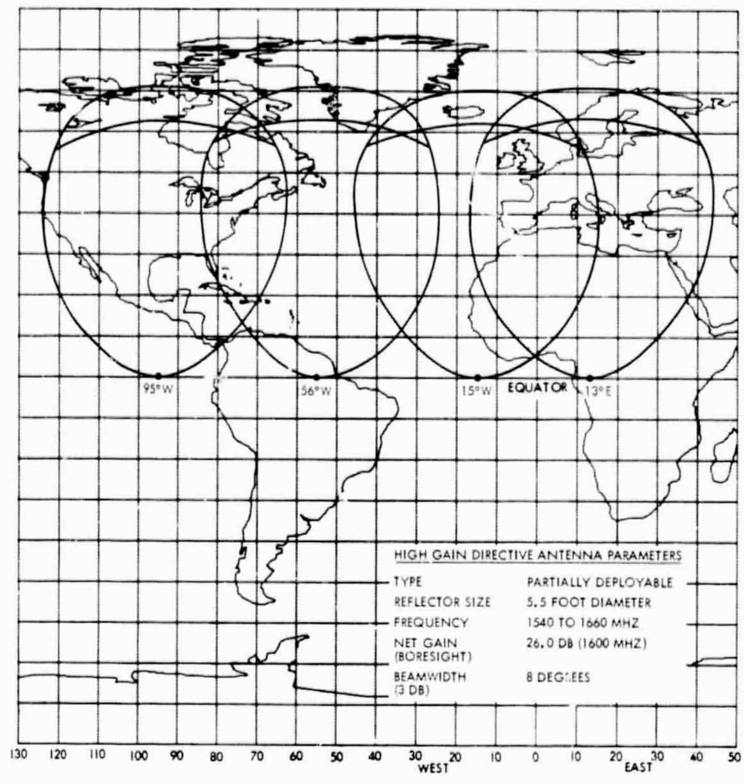


Figure 62. Communications Coverage Supplied by Four Synchronous Circular Equatorial Satellites

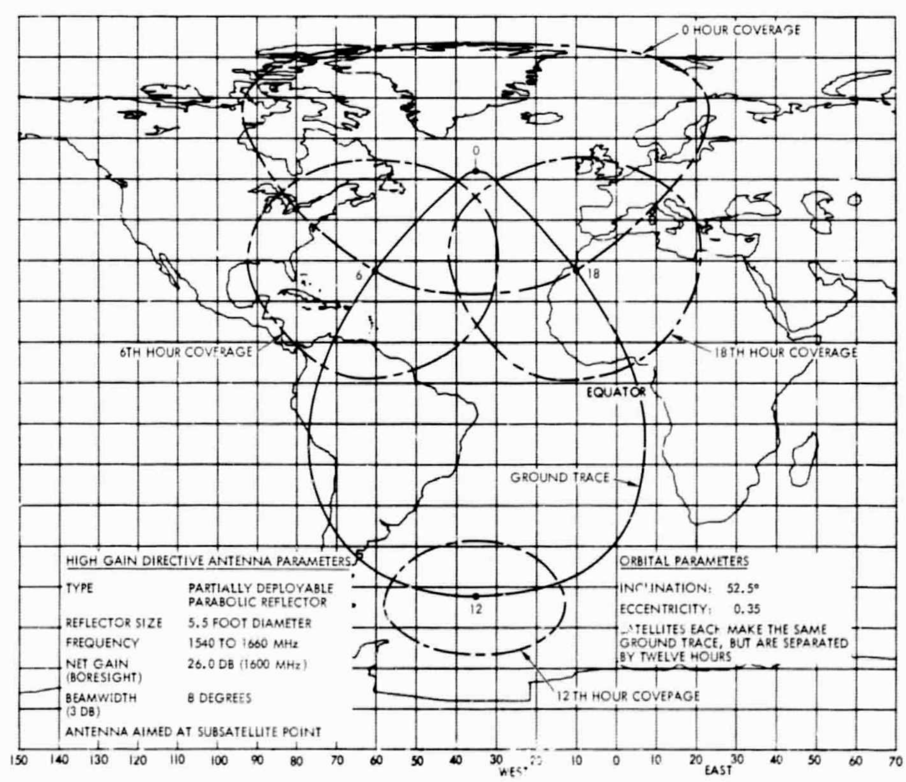


Figure 63. Communications Coverage Provided by a Pair of Satellites in Synchronous, Inclined, Elliptical Orbits.

Finally, the effects of communications antenna pointing inaccuracies are shown in Figure 64. With the present Navigation/Traffic Control Satellite System design, it is expected that the worst case pointing errors would be on the order of 0.5 degree. If the 14° West satellite antenna were pointed approximately 1/2 degree to the right (East) and the 56 degree satellite antenna were pointed 1/2 degree left (West) the communications coverage overlap would obviously get substantially smaller and the "scallop" of no coverage at all in the North Atlantic Ocean just east of Greenland would drop down to some 57 degrees. However, it would still remain above the principal path between New York and London/Paris. Also, if the 56 degree West satellite antenna pointing error was 0.5 degree to the right(East) coverage from this satellite would still be available in the New York area. It can be inferred by inspection from this figure that vertical pointing errors on this order would be even less significant since a northern tilting error uncovers only the low priority equatorial area and the southerly pointing error would simply cause loss of coverage in the area North of 60° North Latitude wherein the performance was considered to be of doubtful quality.

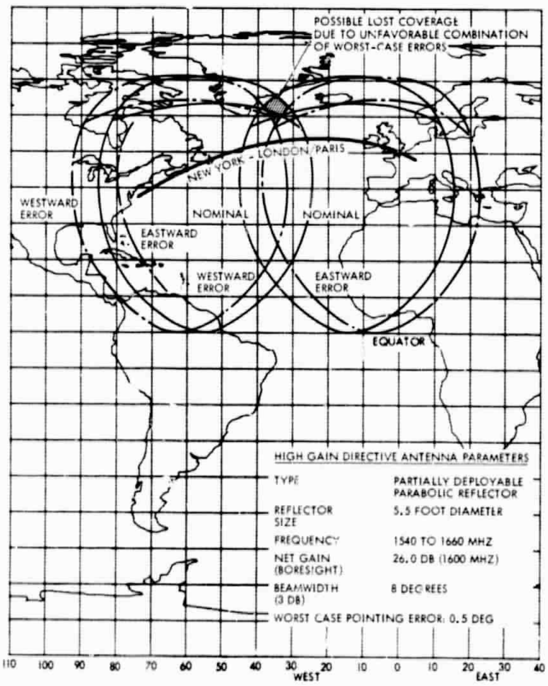


Figure 64. Effects of Communications Antenna Pointing Errors of 0.5 Degree

4.9 REFERENCES

1) J. L. Levatich, "Voice Channel Performance of a VHF Satellite-to-Aircraft Link," Comsat Corporation Technical Memorandum SAD-13-67, July 1967.

2) J. L. Levatich, "Effects of Sea Reflection Multipath Fading on Aeronautical Satellite Service in the 136 MHz Band," Comsat Corporation Technical Memorandum, October 1966.

3) ARINC/Airlines SATCOM Program, Summary of 1967 Activities and Technical Data, 15 March 1968.

4) CCIR, Xi Pleneray Assembly, Oslo, 1966, Vol. IV—Report 205-1, pages 234-256.

5) "A Survey of Ionospheric Effects Upon Earth-Space Radio Propagation," Proc. IEEE, January 1964.

6) G.H. Campbell, "Report for the Experimental Study for NAVSTAR Aircraft Antennas " TRW Systems IOC 7342.1-83, dated 7 June 1968.

7) "Test Plan for NAVSTAR Navigation System," Vol. I, Test Plan Description, TRW Report No. 08710-6023-R0-00, November 1968.

8) D. C. Hogg and W. W. Munford, "The Effective Noise Temperature of the Sky," Microwave Jornal, March 1960.

9) OTM Report, "Impact of Projected Space Services Upon Utilization of RF Spectrum," January 1968.

10) N. Estersohn and A. Garabedian, "Study of a Navigation and Traffic Control Technique Employing Satellites" (Interim Report), Volume III, User Hardware, December 1967. TRW No. 08710-6014-R000.

11) G. W. McClure and J. C. Dute, "Survey and Analysis of Long-Distance Communication Techniques," Institute of Science and Technology, University of Michigan Report No. RD-64-7, May 1964.

12) John Jansen, "Aeronautical Communication Satellites," AIAA Paper No. 8800.5 3-004, May 1966.

13) "Circulation of SATCOM Budget Suggested by FAA," AEEC Letter 66-2-42 (Satcom Newsletter No. 9), July 1966.

14) "Systems Engineering Study of Aeronautical Satellite Services," Final Report to Communications Satellite Corporation, Philco-Ford Corporation, et al, TR-DA1583(1), 15 December 1967.

15) Beranek, L.I., The Design of Speech Communication Systems, Proc. I.R.E. Vol. 35, September 1947, pp 880-890.

16) Systems Engineering Study of Aeronautical Satellite Services, Final Report to Comsat Corp. TR-DA 1583, Vol. III, Philco-Ford Corp., 15 December 1967.

17) Kryter, K.P., "Validation of the Articulation Index," Journal Acoustical Society of America, November 1962.

18) T.K. Foley, B.J. Gaumond, and J.T. Witherspoon, "Optimum Power Division for Phase-Modulated Deep-Space Communication Links," IEEE Transactions on Aerospace and Electronics Systems, May 1967.

19) "Unpublished Notes on World-Wide Airplane Traffic," The Boeing Company, Received 6 August 1968.

5. POSITION DETERMINATION SUBSYSTEM ANALYSIS

5.1 INTRODUCTION

5.1.1 Ground Rules

This section presents in summary form the results and conclusions of the studies performed on different navigation satellite concepts for air traffic control in the Navigation/Traffic Control Satellite Mission Study. In the Navigation/Traffic Control Satellite Mission Study, several ground rules were imposed. The system for position determination (by an arbitrary user) and surveillance (of aircraft by an air traffic controller) is to be designed for initial operation of the North Atlantic Ocean area. It is also to have the capability of growth to cover the entire world, except in the polar regions. The reason for not including the polar regions is that there is a small amount of air traffic in these areas, and many navigation satellite concepts pay a high penalty for operating there. Synchronous equatorial orbits are a logical choice for an initial operational capability since they provide continuous coverage of the area of interest with a minimum number of satellites.

The required capacity of the system, developed in Section 2 of this volume, was based on the projected peak load for air and marine traffic in the North Atlantic Ocean Area in nineteen-hundred and seventy-five. The peak capacity rate for the Navigation Traffic/Control Satellite System is approximately 10,000 fixes per hour for air traffic control surveillance (required), approximately 16,000 fixes per hour for air navigation (desired), and 31,000 fixes per hour for position determination by marine users for purposes of surveillance and navigation (desired, but not required). This level of system capability has an effect on the characteristics of active systems that will be designed for operation in this environment since active systems are subject to saturation effects.

Since the VHF bands are already in use for air traffic control purposes, they present certain attractions for use in satellite navigation. In addition, there is an area in L-band allocated for use by experimental satellites which could be used for navigation purposes. There is a possibility that higher frequencies (C- or X-bands) might be utilized. However, the considerations of space loss makes these higher frequencies very unattractive for small mobile terminals. As discussed in Section 1, system tradeoffs associated with the dependence of satellite transmitter power, ionospheric refraction errors, and cosmic noise on frequency turn out to make L-band very attractive for range measuring systems. The dependence of accuracy on frequency in interferometric systems for a fixed baseline length turn out to make C- or X-band mandatory for interferometric concepts, thus necessitating additional expense for user antennas.

The attractiveness of the navigation satellite system is strongly dependent on the number of users which can work with it. To maximize the number of users, one of the major goals of the study was to develop concepts that would minimize the user equipment cost. A goal of $2,000 for a set of low cost user equipment was established as desirable at the beginning of the study. Low gain antennas are desirable due to cost, weight, and complexity considerations. The choice of low gain antennas at the user plays an important role in the design of an RF navigation link for the system in general and the active system in particular.

One additional ground rule discussed in Section 2 is reflected in a requirement to make the surveillance process for air traffic control independent of information from the pilot and from most aircraft equipment such as inertial navigators. It was assumed that altitude would be available for use in determining position with measurements from navigation satellites. However, other information from the aircraft in the form of aircraft velocity, air data information, or inertial navigator outputs should not be used for the surveillance function.

5.1.2 Summary of Navigation Concepts

This section summarizes the characteristics and salient points associated with each concept that was considered in this study. In discussions that follow, the word "passive" implies a concept where the user does not have to transmit or transpond a navigation signal in order to determine his position. An active concept is one where the user must transmit or transpond a signal in order to determine his position. The process of transmitting or transponding for purposes of navigation is assumed here to be independent of any transmission by the user for purposes of communications. The distinction between active and passive is perhaps best illustrated by examples. For example, the user could determine his position using a passive concept and then transmit it to a central (air traffic control) facility over a communication link. In an active concept, the user would receive a signal and transmit another signal to a satellite. The transmitted signal would then be used to determine position at a central point. If the user is to obtain the reports of the position determination for an active system, this information must be transmitted to him over a communication link from the central point. In the passive system, a communication link is used to transmit the equivalent of position reports from the user to the central facility. In the active concepts, a communication link is used to transmit the position determination to the user.

5.1.2.1 Passive Ranging

The passive ranging concept uses either two measurements of range to different satellites and one measurement of user altitude or three measurements of range to different satellites to determine position. A modification of this concept (which does not require that the user be synchronized with the satellite clocks) uses three measurements of relative range to different satellites and a measurement of user's altitude or four measurements of relative range to different satellites to obtain position. This concept is outlines in Reference 1. Since the user equipment and the system concept are much simpler and/or more accurate if a synchronized user clock is not a required part of the system design, this approach will be used to establish a system design for determining the desirability of a passive ranging concept. Consequently, although at least two satellites would suffice to give accuracies on the order of 0.2 mi/hr, three satellites in an equatorial orbit will be postulated for North Atlantic coverage. Inclined orbits are desirable if the coverage area is to include the equatorial regions of the North Atlantic area. They also provide significant accuracy improvement, particularly for altitude measurement. Eleven to eighteen satellites are required to extend the coverage of the system worldwide.

The passive ranging concept is capable of earth coverage operation at L-band with satellite transmitted powers of the order of 50 watts. The ephemeris data for the satellite that is needed by the user to determine his position can be transmitted over the navigation channel by time division multiplexing with navigation transmissions. The user equipment for this concept consists of a receiver which demodulates the incoming signals, a buffer or preprocessor, a computer for performing position determination, and a display unit. It is possible to use a passive ranging concept with different degrees of user equipment complexity. For example, the user, such as a supersonic transport, might have a general purpose computer and a fairly complicated display unit, while a user such as a fishing boat might use a desk calculator and a much simpler display unit. With the addition of accurate stationkeeping of synchronous equatorial satellites, the user can use tables or very simple manual computations and still obtain accuracies of 1 n mi or better. Consequently, the passive ranging concept has a significant degree of operational flexibility.

The accuracy of a passive ranging concept is strongly dependent on locations of the satellites relative to the user. The absolute navigation accuracy of a passive ranging concept can be better than 0.01 n mi. With certain procedures, the accuracy of a passive ranging concept for the same constellation can approach 0.005 n mi. Finally, beacons can be placed on the ground to further improve accuracy in local areas, if desired.

Several modulation schemes can be used in a passive ranging concept. If a "chirp" pulse compression modulation scheme is used, a high range measurement rate is otabinable in that one range measurement can be obtained every time the satellite transmits a pulse (although in practice this rate is decreased by a factor of two or three to permit the use of coincidence detection techniques); however, this modulation technique requires high peak power (of the order of 20 kw) in the satellite for compression ratios permitting low cost hardware. Multiple tone CW ranging concepts or pseudo-random noise (PRN) coding techniques (described in Reference 1) require longer acqusition times and higher cost user hardware than the BINOR code described in Reference 1. Since the BINOR code will permit a range measurement at a rate faster than once every two seconds, the rate is suitable for use by a high speed vehicle such as an SST if the effect of vehicle velocity is included in the position determination process. For a fixed satellite power this would be more difficult with the PRN or CW modulation techniques due to their slower measurement rates and the resulting longer extrapolation period. Consequently, the BINOR code appears to be the most attractive modulation concept for passive ranging.

With a passive ranging concept, some form of reporting is required for surveillance by an air controller. This will be accomplished by transmitting the raw range measurements. This enables the traffic controller to determine the aircraft's position independently of the aircraft's computer.

These considerations and the information presented in subsequent sections of this report lead to the conclusion that the passive ranging concept should be selected for position determination and surveillance in air traffic control.

5.1.2.2 Active Ranging

The active ranging concept uses measurements of the round-trip time from the ground station to a satellite and user to obtain measurements of the distance between the satellite and the user. Again, the L-band region is optimum, and this discussion is based on the hypothesis that the system operates at those frequencies. Two methods for employing this concept were considered in this study. One involved the use of a pulse compression modulation scheme with the pulse compression performed by a linear FM sweep or chirp transmitter located in the satellite. The other pulse compression system featured the use of a digital matched filter located at the ground station. Each of these modulation schemes requires at least two satellites and user altitude information to obtain a position fix in the North Atlantic Ocean area. Eight to fifteen satellites are required to cover most of the world; again, the constellation selection depends upon user requirements such as accuracy and redundancy. Two other modulation schemes, CW multiple tone ranging and coded phase modulated signals, were also considered in an active ranging concept. However, consideration of the CW concepts was dropped since they require several seconds for signal acquisition.* Approximately ten

*At satellite transmitter power levels comparable to the passive ranging concept.

thousand position fixes per hour are required by the position determination system, which makes this (relatively) long acquisition time unacceptable. If the estimate of the total number of fixes per hour required in the North Atlantic Ocean area will be reduced by order of magnitude, then with the use of CW multiple tone ranging or the BINOR code could be considered.

If range measurements are made in a sequential manner by waiting until one range measurement is completed before the signal for another range measurement is transmitted, then a fix rate capacity of the order of 50,000 fixes per hour will result due to the round-trip time from the ground station to the satellite to the user and back of approximately 0.4 second. To come closer to meeting the capacity requirements with one group of satellites in an active ranging system, a technique of interleaving the transmissions associated with different range measurements was developed. This technique features the transmission of several range signals intended for different users in bursts and then waiting until the replies from the users are received before other signals are transmitted. The transmission of the signals in bursts with the size of the bursts and their location in time fixed so that interference between different ranging signals does not occur permits the capacity of the system to be increased considerably. Without transmitting the signals in bursts, the maximum fix rate is about two fixes per second. If the transmission timing is optimized by accounting for the fact that the user is located near the surface of the Earth and the transmission of signals is scheduled so that interference does not occur, a maximum rate of approximately 5.5 fixes per second can be obtained. If more precise a priori information regarding the user's position is incorporated into the scheduling of the ranging transmission, then the fix rate can be increased by approximately 12 fixes per second. This scheduling of ranging transmissions will involve a complex computer program at the ground station. By using these interleaving techniques for transmitting ranging signals, the capacity of an active ranging system can be increased considerably. However, there will always be a point in such a system where saturation will occur. At this point, the navigation system will be unable to handle all requests for fixes unless additional transponders are used.

To investigate the feasibility of the active ranging concept, two modulation techniques were examined. The pulse compression concept features the use of an FM pulse compression signal generated in the satellite. For this concept, the IF bandwidth is 2.2 MHz, the processing gain is 100, and user noise temperatures is assumed 518°K. These appear to be representative design conditions. The fix rate is assumed to be 10,000 fixes per hour. The operation of the system at synchronous altitude requires a peak power from the satellite of 18.6 kilowatts at L-band and approximately 240 watts of average RF power. While the use of a pulse compression modulation scheme permits rapid acquisition of the transmitted signal by the user, the high satellite power requirements make this scheme very unattractive. In addition to the high satellite power requirements, there is also a transmitted peak power requirement at the user for 53 kilowatts. While the duty cycle and therefore the average power at the user is low, this high peak power (which is due to part to a relatively low signal-to-noise ratio at the user and satellite receivers) makes the system even more undesirable.

The technology associated with large scale integrated circuits has advanced in recent years to the point where digital matched filters which use coded phase signals and provide processing gains of the order of 2,000 are feasible. Although these filters are not simple, if one were used in a ground station, certain problems associated with the FM pulse compression active ranging concept could be alleviated. The average power could be dropped to the order of 40 watts in the satellite. The peak power required in the satellite is an undesirable 3.1 kilowatts. Addressing among the different users could be handled by using individual codes with different transmissions. If it becomes feasible to put a digital matched filter in each user, then it is possible to reduce the transmitted power required at the satellite down to an average of about 20 watts and a peak of 1.8 kilowatts.

With an active ranging concept, the accuracy is comparable to that associated with the passive ranging concept. (Compensation for biases due to instabilities in the user's clock is not required.) The major error source is instability in the repeater delay, which can be controlled to difference degrees by calibration procedures.

As long as the capacity requirements do not outgrow the system design, the active ranging concept is attractive for surveillance to a degree comparable to that of the passive ranging. It is not nearly so attractive for navigation as passive ranging. It has inherent problems with saturation and with high satellite transmitter power requirements for systems involving satellites at synchronous altitudes.

5.1.2.3 Active Range and Angle Measuring Concept

The active range and angle measuring concept uses an FM pulse compression modulation scheme with a transmitter and receiver in the satellite to measure range to the user in an active manner. The user transponds the ranging signal in the same manner as the active ranging concept. In addition to transponding the ranging signal, the user also transmits to the satellite a CW signal for measuring angle of the line of sight with two sets of interferometers. The ambiguities in the interferometer can be resolved by using both short and long baselines or by a priori information. The time interval between the transmission and receipt of the signal at the satellite and the received phase information from the interferometric measuring system are both transmitted to the ground where the position determination is accomplished. The active range and angle measuring concept does not require any inputs from the user to make a position fix. L-band is a reasonable choice of frequency for the ranging system. A choice of higher frequency in X- or S-band for the interferometric signal would be more appropriate due to interaction between requirements for baseline length (in terms of electrical wave lengths) and accuracy. It will, of course, complicate the user hardware by necessitating either high power or high gain antennas.

There are several very complex satellite design problems associated with the concept. The RF systems which process the received information from the users and telemeter it back to the ground are much more complex than those associated with the other concepts. In an interferometric angle measuring system when range information is used at synchronous altitude, 50 microradians of attitude error will cause approximately 1 n mi error in position determination. The stability of the booms on which the interferometer antennas are deployed and the design of the attitude control system to attain pointing accuracies of this order present difficult if not insoluble problems. A yaw (angular motion about the local vertical) attitude error of about 285 microradians can also cause a 1-nmi position determination error. It does not appear feasible to control attitude and boom deflections in the presence of disturbances to the levels that are compatible with a 1-nmi accuracy requirement. Consequently, it will be necessary to compensate for these disturbances by measuring signals transmitted from a ground station and using this data to shift the phase of the received signal in the satellite. This compensation scheme which will feature a network of several dedicated ground stations may be feasible (deleting test results would be required to prove it) but is certainly complex and in the end offers a service which is at best for inferior to that available from the ranging systems. The accuracy of an interferometer system in the presence of phase measurement errors is inversely proportional to the baseline (boom) length and to the carrier frequency. However, the problems of complexity of the attitude control system design tends to increase with the boom length. In addition, the compensation system design will depend on the magnitude of the boom deflections and attitude control system errors. Consequently, there exists a set of design tradeoff studies involving these items that must be thoroughly examined before the feasibility of meeting an accuracy requirement of the order of 1 mile with an interferometric system using synchronous satellites can even be estimated. Even if this type of system with compensation was indicated feasible under one set of operating conditions, it would be extremely sensitive to possible disturbances and deviations from these conditions.

If an interleaving scheme for transmitting signals in bursts is used with an active ranging and angle concept, approximately 100,000 fixes per hour can be obtained from one satellite. This is greater than the capacity of an active ranging concept because only one satellite is involved. The satellite and user transmitter power requirements for ranging in the active range and angle concept are similar to those associated with the active ranging concept for a pulse compression ranging modulation system. The increased capacity, however, would tend to increase the satellite average power by almost a factor of two. In addition, the user must transmit the CW signals that are used for angle measurements in the satellite. The user transmitter peak power requirements for these CW signals will depend on the satellite receiver characteristics, the user oscillator stability, and doppler shifts. In this case, where a time interval of the order of ten milliseconds is available to make the interferometric phase measurements associated with one fix, the user transmitter power required for acquisition of the CW signals at the satellite could be larger than the 53 kw associated with the passive ranging concept.

The problems associated with attitude control, boom bending, and design of the satellite RF system put this concept in a position where its feasibility is not likely. In addition, user hardware requirements (power) are very severe. It has the attraction that its capacity is twice that of the active ranging system and that its sensitivity to attitude errors is somewhat less than that of the passive interferometer due to the presence of range measurements. Also, only one satellite is required to determine a user's position.

5.1.2.4 Passive Interferometer

The passive interferometer concept uses a satellite which transmits signals from thw two interferometric baselines. The measurements of the phase difference of the signals from the two baselines provide the orientation of the user's line of sight. An additional altitude measurement will enable the user to determine his position in a passive manner. Some method of ambiguity resolution is needed with this scheme since angle measurements with a very long baseline interferometer are ambiguous.

In the passive interferometer, the sensitivity to attitude control system error and antenna boom deflections is more severe than was the case with the active ranging and angle measurement concept. For the passive interferometer, a 50-microradian attitude or boom deflection error will cause the equivalence of a 1-n mi navigation error at the subsatellite point while a 10-microradian radar error will cause the equivalence of a 1-n mi navigation error at a point where the elevation angle is 10 degrees. These sensitivites are for a satellite at synchronous altitude. A comparison of these numbers with corresponding numbers in Paragraph 5.1.2.3 indicates that range measurement information that is available in the active range and angle concept will decrease the sensitivity to attitude errors. The sensitivity to a yaw attitude error is less in that it depends in a linear fashion on the distance between the user and the satellite local vertical, and it has a maximum value of 1-nmi navigation error per 285-microradian attitude error.

The above sensitivites make it clear that it is not feasible to meet the navigation accuracy requirement of 1-nmi by direct control of the satellite orientation. As was the case with the active angle measurement concept, a compensation technique which will measure the attitude error is required to meet the required navigation accuracy with feasible attitude control system capability. One compensation technique would involve the use of transmitted signals from a network of dedicated ground stations to the satellite. Measurements obtained in the satellite from these signals could then be used to vary the phase and frequency of the transmitter output from the satellite. This type of compensation would introduce serious complexity to both the satellite design and the ground station network. An alternative compensation technique that could be used would involve transmission of information concerning the misalignment of the baseline relative to its ideal orientation over a data link to the user. The user could then make the appropriate compensation in his position determination computations.

Another problem associated with interferometric concepts is the accuracy with which phase measurements can be made at the user. It is possible to measure the phase difference between two sinusoids to accuracies that are much better than 1 degree in a laboratory environment. However, there is considerable doubt that this can be accomplished reliably in an operating environment where the user equipment is not handled in the same careful manner as in the laboratory. The satellite characteristics and phase measurement error enter into the accuracy of an interferometer by the following relationship:

$$\varepsilon\theta = \frac{\lambda\delta\phi}{2\pi D \sin} \tag{30}$$

where

θ = angle between line of sight and baseline

D = baseline length

λ = wavelength of sinusoid carrying phase information

ϕ = phase difference.

The above relationship indicates that it is desirable to use a high frequency for purposes of obtaining high accuracy with a given phase measurement error, however, going to a high frequency requires the use of higher transmitter power levels in the satellite. For frequency in X-band, it is estimated that the required satellite power will be of the order of 330 watts for a two-channel interferometer system.

The user equipment for a passive interferometer would include a receiver that will make the two phase difference measurements and the associated data processing and display equipment for a complex user. The data processing equipment would involve a general purpose digital computer. For a set of simple user equipment, there is a possibility of using less complex data processing equipment which would enable the user to trade computational speed and flexibility for cost.

Thus, the only advantage of the passive interferometer concept is that only one satellite is needed to make a fix. Since this is an extremely complex and expensive satellite, the disadvantages of the technique rule clearly against it.

5.1.2.5 Passive Polar

The "Big Omni" passive polar coordinate system concept uses one satellite to obtain a position fix. User altitude measurements are also needed. The satellite has a single axis interferometer that rotates in the horizontal plane. In this way, the single interferometer is time-shared with the two horizontal axes. The transmitted signal from this interferometer uses a periodic CW phase modulation which is synchronized to the passage of the interferometer baseline through a reference orientation. The received signal yields the bearing and distance from the sub-satellite point after demodulation of the phase modulation signal. A carrier frequency of approximately 30,000 MHz appears to be required to meet an accuracy of the order of 1 nmi. The attitude control system sensitivity and boom deflection problems are also present in this interferometer concept. The design of the user's receiver is quite complex in that it involves three interacting phase lock loops. It is estimated that this concept will be somewhat less accurate than the fixed interferometer technique due to the additional complexity. However, it will not have ambiguity resolution problems. More detailed descriptive analysis and design information for this concept is given in References 12 and 13.

Because of the complexity of the proposed user-receiver design and the questions associated with attitude control system errors and boom deflections, the feasibility of this concept cannot be established in a study of this funding level and scope, but enough work has been done to rule out this technique.

5.1.2.6 The Fan Beam Angle Measuring Concept

The fan beam angle measuring concept uses a spin stabilized satellite which transmits signals from two antennas with orthogonal fan beam patterns. The angular orientation of the line of sight between the user and the satellite can be determined from the time intervals between the fan beam crossing times at the user and at the subsatellite point (or some other reference direction). Once this determination is made, the use of user altitude in addition to the orientation of the line of sight enables the user to determine his position. One satellite is needed to determine position in this concept.

The signal characteristics at the user-receiver depend on the fan beam width (in the narrow dimension of the fan beam) and the angular velocity of the satellite. The fan beam width is inversely related to frequency and to the length of the antennas. An involved design study of the tradeoff between satellite angular velocity antenna length and carrier frequency has been made and is documented in Reference 14. The results are that a carrier frequency of 4 to 8 GHz, a spin rate of approximately 3 revolutions per second and an antenna length of approximately 8 feet are about optimum for this concept. These design conditions imply an antenna pattern beam width of the order of 1 degree. The results in turn specify the video or post-detection bandwidth of the user's received signal. The bandwidth turns out to be of the order of 600 Hz. This signal shape is approximately gaussian, and its rise time will be of the order of 1 millisecond.

The synchronous altitude requirement for accuracy of the order of 1 n mi and a spin rate of 2 revolutions per second imply a requirement for the fan beam crossing time measurement accuracy of the order of 2 microseconds. On the other hand, a rise time of the pulse is of the order of 1.6 milliseconds. Measuring the arrival time of a pulse to 0.1 percent of its rise time puts unrevocable requirements on such receiver characteristics as the threshold stability, the automatic gain control circuit design, and the amplitude stability of the transmitted signal. In addition, as will be shown in Section 4, the measurement of the time of arrival to this level of accuracy will also require extremely high signal-to-noise ratios for a signal with this bandwidth. The requirements for high signal-to-noise ratios are reflected back into requirements for extremely high transmitted power for the satellite. For example, for the power budget in Table 23 which has no margin, the transmitted power requirements turns out to be 890 kilowatts of peak power and 44 killowatts of average power. Large sensitivities to antenna pattern and vehicle attitude misalignment which existed in the passive interferometer also exist here. These sensitivities require that the antenna pattern and spin axis be established to a level of the order of 10 microradians to meet a 1- nmi accuracy requirement. The feasibility of obtaining this accuracy with a deployable antenna (which would probably be necessary with an 8-foot boom antenna that turns out to be an attractive compromise among the boom-length versus beam-width and boom-length versus stress trades that are discussed in detail in Reference 14 and the effects of coning motion of the satellite raise questions about the feasibility of this concept.

The above considerations lead to the conclusion that the fan beam concept is not feasible for navigation using satellites at synchronous altitudes.

5.1.2.7 Long Baseline Interferometric Concepts

Two concepts proposed in Reference 15 were considered in this study. One involved the use of a constellation of four satellites in synchronous equatorial orbits separated by distances of about 1 mile. The relative position of these satellites is chosen so that they form two baselines from which interferometric angle measurements can be made. The fact that a measurement with an interferometer uses what amounts to a measurement of patch length difference or range difference to obtain angle information leads to many similarities between a range difference measurement scheme and this concept. The major source of the differences will involve the satellite constellation, the accuracy, and the signal design. The results presented in Reference 16 lead to the conclusion that the refraction error in an interferometric system due to ionospheric effects will be worse than for a range measuring system. There will also be stationkeeping problems (to maintain baseline stability) and problems associated with control (stability) of the transmitted phase from different satellites. In range and range difference measurement systems, the accuracy tends to get worse as the satellites get closer together. Consequently, it appears that this version of the long baseline interferometer has many similarities to the range measurement concept and involves several additional difficulties not present in the passive range or range difference measurement concepts with larger satellite separation and coded modulation concepts.

Another version of the long baseline interferometer concept uses sequential range measurements from satellites in subsynchronous equatorial and polar orbits. For example, with a 10-hour orbit, range measurements from a satellite at times of the order of 1 second apart will provide a baseline whose length is approximately 1 mile. In some respects, this concept is like the passive range measurement concept in that sequential measurements are made to satellites located in different points. It is also analogous to the transit concept in some respects. There the equivalent of range difference information is obtained by processing doppler data during a satellite's passage over the user. This concept will require about 12 satellites for North Atlantic coverage without redundancy compared with the 4 satellites using passive range measurements required with a constellation in synchronous orbits. Furthermore, the fact that the range measurements are made from satellites separated by distances of the order of 1 mile will tend to degrade the navigation accuracy. These considerations made this concept less attractive than other alternatives such as the passive or active range concepts.

5.2 COMPARISON OF ACTIVE AND PASSIVE CONCEPTS

All position determination systems considered in this study can be divided into two classes. As indicated before, all systems wherein the user radiates an electromagnetic signal care called active systems. In the second, or passive, class of systems, the user does not radiate. This classification refers only to the navigation function and not to the surveillance function. When a system is used for surveillance, all users must of necessity radiate some form of information to the control station. Only the position determination aspects will be considered here. The communcation portion of the surveillance function—autorep—is discussed in Section 2 of Volume II, and Sections 3 and 4 of this volume. The systems can be further classified as range or angle measuring systems. The differences between these subclasses will be discussed in this section of this report, as well as the general characteristics of active and passive systems.

5.2.1 System Capacity

The basic definition of the capacity of a system is the number of users that can be accommodated at one time. This is the maximum number of fixes per unit time the system can provide the total population of users and is called the system fix rate. A second measure of capacity which is useful when making comparisons between systems is the rate at which position fixes can be provided for each user. This is the maximum user fix rate. The capacity of all passive systems is infinite. A passive user system can accommodate every user within its coverage area. Active systems have a limited capacity because there is a limited amount of the frequency spectrum available for use and only a few of the relatively high power channels can be carried onboard a single low cost satellite.

To make a fair comparison between active and passive systems, the total user population and the fix requirements for each type of user must be considered. The reason is that in a passive system, all users could be fixed at the maximum system rate, giving a total number of fixes per unit time of the maximum rate times the number of users. However, many users do not require, and could not effectively use, a high rate of fixes. The fact that the passive system could provide them is in itself of no economic value. To properly compare active and passive approaches, the user fix rate requirements of a postulated population must be derived, then the sum of all user fix rates compared to the system fix rate available from a particular active system. The number of channels the active system needs is the fix rate required divided by the fix rate per channel. The final step is to compare the total active system, which has as many channels as required, with the passive system. In other words, the active system, which will accommodate the postulated population is compared to the passive system. The fact that the passive system has excess unused capacity is important from the standpoint of growth but not for comparing systems for use with a given population. The estimated capacity of each of the concepts under study are shown in Table 14 and described in the following paragraphs.

Table 14. Estimated Capacity of Each Concept Under Study

	User Rate (fixes/sec/user)	System Rate (total fixes/sec)
Passive ranging*	1 fix per 8 sec	Can be as large as desired
Active ranging	----	5 to 12 fixes/sec**
Passive interferometer	>10 fixes/sec	Can be as large as desired
Active interferometer	----	20 to 35 fixes/sec**
Philco fan	2 to 3 fixes/sec	Can be as large as desired

*Four satellite North Atlantic system.

**Depends on extent of a priori information used in ground station software to schedule transmission of signals used for position determination.

5.2.1.1 Passive Ranging

The passive ranging concept developed by TRW uses passive range measurements to a minimum of three satellites to determine position (assuming altitude is known). A number of CW techniques were considered by TRW, including fixed tones, swept tone, and digital code. After careful study TRW selected a digital code system called Binary Optimum Ranging (BINOR). (See Appendix B, Volume III, Reference 1.) The

BINOR ranging code CW system requires that each satellite broadcast for a period of approximately 2 seconds for the user to acquire the carrier, the code, and to make the range measurement. The satellites are time-multiplexed such that 6 seconds are required to measure three ranges with the minimum satellite constellation. The fix rate could be virtually continuous if frequency division multiplexing were used (see Reference 1) but at the cost of more expensive user equipment.

It is possible to construct a passive ranging system which could provide more than ten fixes/sec by simultaneously transmitting from each satellite on a different frequency. Frequency multiplexing, however, would require more complex user equipment and was consequently rejected in favor of time multiplexing.

The second operational constellation for the North Atlantic has four satellites, providing redundancy so the system would be completely operable in the event of a failure of any one satellite and partially operative in case of a double failure. The maximum fix rate for a passive ranging system for the North Atlantic will be one fix per 8 seconds for this comparison.

5.2.1.2 Active Ranging

An active ranging system, for use in the North Atlantic, has been configured, which appears to make the best use of the possible options (Reference 2).

The system operates by making two (assuming altitude is known) range measurements between two satellites and a user. These measurements are made as follows:

a) The ground station selects a user and sends out a ranging message which includes the address of that user.

b) The message is relayed by a satellite to the user.

c) The user receives and relays the message back to the satellite along with altitude data.

d) The satellite relays the message back to the ground station, where the total transit time for the signal is measured.

e) The above sequence is repeated a second time through a different satellite.

Since the positions of the ground station and the satellites are known, the range to the user can readily be found.

If a constellation of three equatorial synchronous satellites at 10 degrees, 25 degrees, and 60 degrees west longitude is considered (for redundancy) the round trip time for a ranging message is between 484 and 552 msec with a total possible variation due to user location of ±18 msec. The General Electric approach was to send out the two ranging messages displaced in time by a small amount (about 90 msec is required to avoid interference) and do nothing until the messages returned. Since the GE system used 5, 600 n mi satellites, it could provide four position fixes per second (14, 400 fixes/hour). If the same technique were used at synchronous altitudes, the fix rate would drop to about 1. 7 fixes/second (6, 000 fixes/hour).

A North Atlnatic user population and user fix rate requirement has been established which shows that the probable fix rate requirements in 1975 will be in the vicinity of 3 fixes/second (10, 000 fixes/hour), which indicates that a minimum of two channels would be required for the General Electric method.

As previously indicated, it is possible to greatly increase the fix rate of an active ranging system by interleaving messages for different users, that is, to so regulate the initiation time of each message that many messages may be in transit at one time without interference at any of the receivers in the system. This possibility was studied in Reference 3, where it was concluded that as many as 12 fixes/second was possible if the ground station could simultaneously receive and transmit. If simultaneous transmission and reception were not possible, the maximum rate would be 7 fixes/second. These rates are for the constellation of three synchronous equatorial satellites mentioned earlier and for a ranging message length of 10 msec, which appears to be well within reason (References 4 and 5).

These rates are achieved by pre-computing the transmission times and times of arrival at each receiver in the system before a ranging message is transmitted. The satellite-to-user transmission time is estimated to within ±1 msec, which is equivalent to a ±160 n mi position uncertainty. The message is broadcast at the earliest possible time when it will not interfere with preceding messages. When each message is sent, its time of arrival at each receiver is reserved for that message alone. This technique results in a nonconstant fix rate that makes optimum use of the system by not allowing it to remain idle.

5.2.1.3 Passive Interferometer

In a passive interferometer system, the signals are broadcast from the interferometer angennas at the satellite to the user where a phase comparison is made. The passive polar concept also functions in a similar manner with added complexity in the user's receiver due to the nature of the signal.

Constant frequency signals cannot be broadcast from each antenna simultaneously because this would only produce refraction patterns at the earth's surface, and the signals from the two antennas could not be separated. Two approaches have been suggested in Reference 7: one is a switched interferometer where the signal is transmitted alternately from one antenna to the other; the second is double side-band Servodyne interferometer developed by Westinghouse.

In either case, the fix rate of the system is very high and once the signal is acquired in the receiver, position may be almost continually estimated. The limitation in the system will be at the level of computation. A high speed digital computer could revise the position estimate at a rate of about 10 times per second if it were required.

The exact fix rate depends somewhat on the particular mechanization but will be considered to be 10 fixes/second for high accuracy user in this comparison.

5.2.1.4 Active Interferometer

An active interferometer plus ranging system was studied by Westinghouse and reported in Reference 6. In this system, each user was alerted via a VHF communications channel that an active ranging pulse would soon arrive. The user would then transpond the ranging message back to the satellite in the same manner as other active ranging systems described in Paragraph 2.1.2. Immediately after relaying the ranging message, the user would generate a CW pulse of unmodulated carrier for angle measurement. The interferometer antennas receive the signal, and the relative phase is measured to determine the angle of the line of sight to the user with respect to the interferometer sensitive axis. The phase angle information is then transmitted to the ground station where user position is computed.

The capacity of this system is essentially twice that of the active ranging system since a user need only be interrogated through one satellite. The ranging message format can be identical to that of the active ranging system of Paragraph 2. 1. 2, and in addition, the user generates an angle pulse (Westinghouse states the angle pulse should be 7-msec long) which immediately follows the transponded ranging message. This yields a total message length of about 10-msec from the ground station to user and 17 msec from user to ground station. Allowing a ± 1 msec uncertainty in estimating satellite to user transmission time (which in the worst case is 160-n mi), the system fix rate will be 25 fixes/second.

5. 2. 1. 5 Fan Beam Angle Measurement Concept

The fan beam angle measurement concept developed by Philco is a passive system in which the time at which a rotating antenna beam sweeps by a user is compared to the time of a reference signal. This is done with two beams which are at right angles to each other. In concept it is like a three dimensional VOR system. According to Reference 8, the satellite which contains the fan beam antennas will rotate at 12 to 18 radians/second. It is possible, in principle, to get a position fix on each rotation; therefore, the maximum fix rate is 2 to 3 fixes/second.

5. 2. 2 Ground Station Software

The ground station provides different services for each concept, therefore, the computer requirements are somewhat different. Table 15 summarizes the functions which are performed in the ground stations for each concept.

The crosses in Table 15 are the functions required for position determination alone. When surveillance is added to the system requirements, the ground station must also perform the functions indicated by the circles. It would appear that passive ranging is the least demanding system and an active interferometer the most demanding of the concepts.

Table 15. Ground Station Functions for Different Concepts

	Passive Ranging	Active Ranging	Passive Interferometer	Active Interferometer	Philco Fan	Passive Polar
Position Determination for N Satellites*	N = 4	N = 3	N = 2	N = 2	N = 2	N = 2
User Roster Keeping	0	X	0	X	0	0
Interleaving Calculation		X		X		
User Position Calculation		X		X		
Satellite Attitude Compensation			X	X	X	X
User Position Log	0	X	0	X	0	0
Satellite Clock Update	X				X**	

* Redundant North Atlantic Coverage

** Calibration of reference pulse in fan beam concept is analogous in many respects to the satellite oscillator calibration in a passive ranging concept.

X - Performed by ground station for position determination function.

0 - Performed by ground station when passive concept is used as part of surveillance system.

5.2.3 Radio Frequency Links

5.2.3.1 Comparison of System Links

The characteristics of the RF links for each concept are somewhat different. They are summarized in Table 16. The power required at the satellite and user is discussed in the next two sections.

5.2.3.2 Average Power Considerations

The average satellite prime power requirement is one of the most important parameters of comparison because of its significant effect on satellite cost and reliability. An estimate of the average satellite transmitter input power for each concept is shown in Table 17. Only transmitter output power is shown. When divided by the overall efficiency, the transmitter power represents more than 90 percent of the total power required from the prime supply. The satellite to ground station line is only a few watts in each case because a very high gain antenna is available at the ground station. To find the prime supply requirements, an efficiency of 35 percent (Reference 5) can be assumed for the pulse systems and the fan beam, and 23 percent (Reference 1) for passive ranging. The power budgets for the satellite-user and user-satellite links are discussed further in Section 4.

Note that for active systems, the average power is proportional to load. If more or less fixes are required, the power can be scaled proportionally.

5.2.3.3 User Power

The user transmitter peak power input requirements for the two active systems are 52 kw for active ranging and a similar amount for the active interferometer.

5.3 COVERAGE CONSIDERATIONS

5.3.1 Satellite Altitude

A North Atlantic system is best served from the point of view of coverage by satellites in synchronous equatorial orbits because far fewer satellites in these orbits are required to give continuous coverage. This fact can be proved by the following argument: It is obvious that the most efficient system (in terms of numbers of satellites) is one in which all

Table 16. Summary of RF Link Characteristics

	Ground to Satellite	Satellite to User	User to Satellite	Satellite to Ground	Carrier Frequency
Passive Ranging	PPM time and ephemeris data	Binor code ranging and ephemeris data			L-band
Pulse Compression Active Ranging	Rectangular pulse ranging message	Dispersed FM pulse ranging message	Dispersed FM pulse ranging message	Rectangular pulse ranging message	L-band
Passive Interferometer	Time and ephemeris data Compensation signals	Time and ephemeris data DW angle measuring signal			S- or X-band
Active Range and Interferometer	Compensation signals Rectangular pulse ranging message	Dispersed FM pulse ranging message Alert signal	CW angle measurement signal and ranging signal	Rectangular pulse ranging message and user angles	C-band
Philco Fan	Compensation and ephemeris data	CW angle measurment signal Ephemeris and compensation data			C- or X-band
Digital Matched Filter Active Ranging	Phase-coded ranging signal	Phase-coded ranging signal	Phase-coded ranging signal	Phase-coded ranging signal	L-band
Passive Polar	Ephemeris data and compensation signals	Sinusoidal phase modulated CW signals			X- or K-band

Table 17. Satellite Power Requirements

	Transmitter Output Power*** (watts) for 1 n mi Accuracy	
	Peak	Average
Passive Ranging	50	12.5****
Pulse Compression Active Ranging*	18,600	990
Digital Matched Filter Active Ranging*	3,100	155
Receiving Interferometer**	250	
Transmitting Interferometer	330	110 (25% duty cycle)
Philco Fan	890,000	44,500

*12 fixes/second

**VHF satellite to user link used to activate user for 25 fixes/second.

***These numbers are derived in Section 4.

****Based on each satellite (in a constellation of four satellites) transmitting one quarter of the time.

satellites are always available for use in the area of interest. A satellite is always available to cover a given area only at synchronous altitude and then only when its inclination is such that it always remains in view. The area of required coverage is up to 70° North latitude in the North Atlantic. A satellite at synchronous altitude can cover an area of 71.5 degrees around its subsatellite point when the minimum elevation angle of the line of sight is 10 degrees. Therefore, the satellite orbit cannot be allowed to be inclined more than 1.5 degrees and still give continuous coverage in the area of interest. Thus, synchronous equatorial satellites are the most efficient choice.

If the system were expanded to world-wide coverage, the above argument is no longer valid.

5.3.2 Constellations

The concepts have somewhat different requirements for satellite constellation. The minimum number of satellites, which must be simultaneously in view from the user knowing his own altitude are as follows:

a) Passive ranging - 2 for 0.2 n mi/hr accuracy, 3 for higher accuracy

b) Active ranging - 2

c) Others considered - 1

It seems unlikely that a system would be put into operation without in-orbit redundancy. Redundancy would require a minimum of one extra satellite in-orbit, for each concept.

The accuracy of the two ranging concepts is sensitive to the angular separation between lines of sight from the user to the satellites. Reference 9 shows that an acceptable spread between the outermost satellites for ranging systems is 50 degrees for redundant coverage over the North Atlantic. The active system constellation would use satellites at 10-, 35-, and 60-degree west longitude. The passive system is 10-, 27-, 43-, and 60-degree west longitude. A table summarizing the number of satellites required for worldwide and North Atlantic Ocean area coverage is given in Table 18.

Table 18. Synchronous Altitude Satellites

	North Atlantic		Worldwide (excluding polar areas)	
	Minimum	Redundant	Minimum	Maximum Hz desired for accuracy measurements and/or redundancy
Passive Ranging	2 for Aircraft, 3 for Ships	3 to 4	11	18
Active Ranging	2	3	8	15
Passive Interferometer	1	2	4	7
Active Interferometer	1	2	4	7
Passive Polar	1	2	4	7
Fan Beam	1	2	4	7

5.3.3 Ground Station Networks

Each of the concepts requires a central ground station and several substations, but the requirements for each system are different. The software functions which are required at the ground station are summarized in Table 15. The equipment required at the control station and the substations is summarized in the following paragraphs. This information is primarily from Reference 10.

5.3.3.1 Passive Ranging

We have shown (Reference 1) that a North Atlantic passive ranging system requires a central computational facility, a command and telemetry station, and can have high accuracy tracking units, three tracking stations. (It is possible that one site would suffice, but this has not been proven.) The command the telemetry station, the computational center, and one of the tracking stations could be located at one site. Then only two remote locations are required.

The central computational center receives data from the tracking sites and telemetry station, and computes satellite ephemeris and oscillator drift for transmission to the satellites from the command station.

The command and telemetry station receives ephemeris and clock update data from the computational station and relays it to the satellite. Stationkeeping, failure detection, and system performance are also controlled or monitored by the command/telemetry station.

The tracking stations are equivalent to a high class user. The prime function of the station is to receive the range data from each satellite and relay this information to the central computational facility.

Single, relatively simple fixed antennas are required at the tracking stations and a single steerable high gain antenna (30 ft L-band) at the command/telemetry site.

5.3.3.2 Active Ranging

An active ranging system requires a much more complex central ground station than passive ranging, because, in addition to satellite ephemeris and housekeeping functions, the station must perform position computations and keep track of all the users.

A total of three tracking stations are required and, as in the case of passive ranging, these stations are essentially high class users which transpond ranging signals that originate at the control station.

Since at least two, and probably three, satellites are in continual use, two or three high gain antennas are required at the control station. Each antenna would probably have its own receiver, while the transmitter could be switched from one antenna to the next.

5.3.3.3 Passive Interferometer

A passive interferometer requires a central control station with command, telemetry, and computational facilities. This system also requires at least three calibration and tracking stations, one of which could be located at the central station. Information transfer to the central site must be at a much higher rate then for passive ranging. The other two must be located of the order of 1000 miles from the central station.

The calibration and tracking stations transmit a signal which is received by the interferometer. These signals are used to compensate for satellite attitude and antenna distortion errors. For range tracking, the satellite must be equipped with a transponder, and each tracking station must have a tracking radar with a high gain antenna. It may be possible in a lower accuracy system to determine satellite position by passive angle measurement.

The central ground station must compute satellite ephemeris and monitor system performance. Only one antenna is required for the central station.

5.3.3.4 Active Interferometer

An active interferometer requires the same three tracking and calibration stations and a central station as the passive interferometer. The central station is more complex because it must perform user position computations and keep track of all the users just as in the case of the active ranging system.

5.3.3.5 Fan Beam Concept

The fan beam satellite is a passive angle measurement scheme, and as such requires the same type of ground network as a passive interferometer. The calibrations are different, but it appears as though three stations would be adequate.

5.3.3.6 Passive Polar

The ground station problems associated with the Passive Polar concept are similar to those associated with the passive interferometer and for fan beam concepts. The orbital and attitude ephemeris data must be determined by the ground station network. Suitable compensation signals must be sent to the satellite to control the modulation of the navigation signals. To preserve a major attraction associated with the Passive Polar concept in that minimum user computation is required, it appears to be desirable to compensate for any attitude control deviations by varying the signal transmitted from the satellite.

5.4 NAVIGATION LINK DESIGN CONSIDERATIONS

5.4.1 Introduction

This section discusses several important factors relating to the navigation link rf design. Primary considerations are the choise of the carrier frequency and the interaction of measurement accuracy, transmitter power, etc., shown in the power budgets associated with the navigation links for the different concepts. The satellite-to-user and user-to-satellite links are most important as far as transmitter power is concerned due to the desire for a low gain antenna on the user as a result of cost and aerodynamic drag considerations. This ground rule was discussed in Section 5. A user antenna gain of 4 db based on results in References 1 and 19 is assumed here. The satellite-ground station links (which are required with active systems) that are used for navigation transmissions can use high gain antennas and low noise receivers at the ground station to reduce the satellite transmitter power requirements to the order of several watts at L-band for this link. In addition, the availability of high gain antennas (of the order of 45 db) at the ground station makes the transmitted power requirements at the ground station of the order of 50 watts. Therefore, most of the discussion in this section will be devoted to the more critical links between the user and the satellite and the results presented in Section 5. 2. 2. The satellite-user links for the passive ranging, FM pulse compression active ranging, digital matched filter active ranging, passive interferometer, and spinning fan beam concepts are presented in the separate subsections devoted to these concepts. The pertinent characteristics associated with user-satellite links in the FM pulse compression and digital matched filter active ranging concepts are also presented here. A detailed analysis of the power budget for the passive polar concept was not derived in this study because work by other participants in the Navigation/Traffic Control Satellite Mission Study led to the conclusion that the feasibility of this concept is in doubt and several important questions cannot be resolved with the level of effort available for this study (see Paragraph 5. 1. 2. 5).

The discussion of the power budgets is based on the link equation presented below:

$$P_{sr} = \frac{P_{st} G_t G_r \lambda^2}{L_T (4\pi R)^2}$$

where

P_{sr} = received signal power at the receiver rf input stage

P_{st} = transmitted signal power at the antenna input

L_T = link losses

λ = wavelength of carrier

G_t = transmitting antenna gain

G_r = receiving antenna gain

R = distance between transmitter and receiver.

Quantities called the path loss and space losses are defined as follows:

$$L_{SP} = \left(\frac{\lambda}{4\pi R}\right)^2 = \text{space loss} \tag{31}$$

$$L_{PA} = \frac{L_T G_t G_r \lambda^2}{4\pi R^2} = L_T G_t G_r L_{SP} = \text{path loss} \tag{32}$$

The noise (spectral density) at the receiver input terminals is the other important factor. It will be represented by the equivalent noise temperature at the rf input stage in a conventional manner (see Volume 1 of Reference 1 and Reference 17), viz.,

$$T_N = \frac{1}{L_{rf}} T_{sky} + (FL_{rf} - 1) T_o \tag{33}$$

T_N = equivalent noise temperature at rf input stage

L_{rf} = user rf circuit losses (from receiving antenna to receiver input)

F = receiver noise figure

T_{sky} = equivalent noise temperature at antenna input representing effects of ground radiation into antenna main beam and side lobes, galactic noise, solar radiation (which is negligible in this study), and atmospherically generated noise

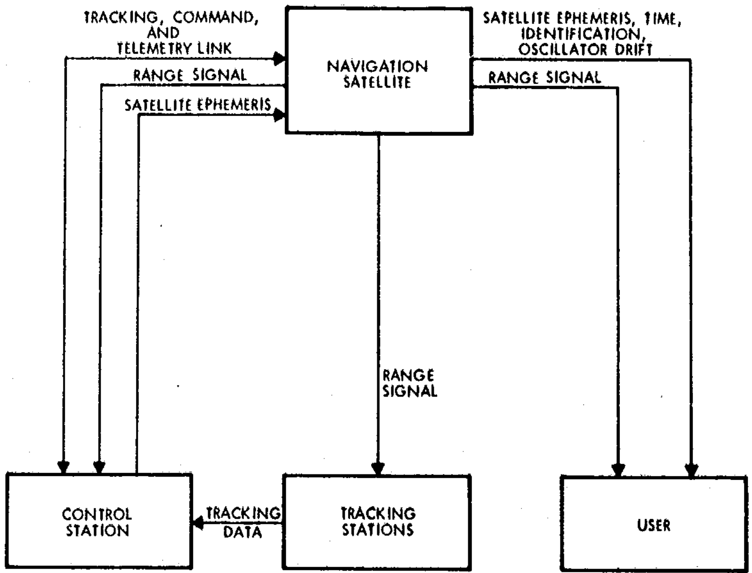
The user antenna gain is assumed to be 4 db based on the results presented in References 1 and 19. The value of 4 db refers to the peak gain of the user antenna which will be valid when user antenna has the optimum orientation. Obviously, this will not always occur due to different elevation angles of the line of sight as the user changes his position and due to user maneuvers. In a practical case, a margin must be allowed in the link design for a nonoptimum orientation of the line-of-sight relative to the user antenna. A suitable margin for this type of antenna gain degradation appears to be from 1 db to 3 db. The margin varies over these limits due to the possibility of partial compensation by using multiple antennas with different orientations on the user or steering the user antenna to some extent. In the power budgets derived in this section, this effect of user antenna orientation relative to the line-of-sight is not included since it is not a major factor in the comparison of the different concepts. This factor will affect all concepts in more or less the same manner. In the links between the user and satellite, the satellite antenna gain is assumed to be 16 db for all concepts except the spinning fan beam. For L-band, this assumption is supported by measurements of the antenna designed for the Advanced Pioneer satellite. For other frequencies of interest such as S- and X-band, it is assumed that this gain can also be attained. Circular polarization is assumed for both the satellite and user antennas. At synchronous altitude, the maximum slant range is 22,700 n mi. Since the spinning fan beam concept requires a satellite antenna whose pattern is in the shape of a fan, a narrower beam width in one dimension is required and a gain of 29 db is assumed for the satellite antenna. This is representative of a pattern 1.0 degree wide in the narrow dimension and 18 degrees wide in the broader dimension.

5.4.2 Navigation Link for the Passive Ranging Concept

A functional diagram of the links in the passive range (or range difference) measuring system is shown in Figure 65. This functional diagram illustrates a design concept that was developed in Reference 1. The design study in Reference 1 is the source of most of the information used to compare the passive ranging concept with other concepts. The BINOR code modulation technique is used here as a baseline as a result of the work in Reference 1 (see discussion in Paragraph 5.1.2.1). All of the links shown in Figure 65 are L-band except for the S-band tracking, telemetry, and command link. A diplexer is used in the satellite.

The losses associated with the range signal or navigation link are shown below:

Satellite diplexer	=	-1.0 db
Polarization and antenna losses (at user)	=	-1.0 db
User cable and input circuit	=	-0.8 db
Atmospheric attenuation	=	-1.0 db
Total link losses = L_T	=	-3.8 db
Space loss L_{SP} (at L-band)	=	-188.6 db
Path loss L_{PA} (at L-band)	=	$-L_{SP} + G_r + G_t - L_T$ = -172.4 db



NOTE: THERE WILL BE AT LEAST TWO TRACKING STATIONS AND THREE SATELLITES IN A NAVIGATION SATELLITE NETWORK

Figure 65. Functional Diagram of Passive Ranging Concept

For the passive ranging concept, the sky temperature T_{sky} is assumed to be $80^{o}K$. This result is made up of the following components:

Galactic noise	$-20^{o}K$
Ground noise radiation into side lobes or main beam	$-30^{o}K$
Atmospheric noise	$-30^{o}K$
Solar radiation	-negligible
T_{sky}	$= 80^{o}K$

The use of $L_{rf} = 0.8$ db (rf circuit attenuation) and a receiver noise figure $F = 5$ db in Equation (5-4) yields a noise temperature T_N of $743^{o}K$.

There are four phases associated with the process of making one range measurement: carrier acquisition; carrier tracking after acquisition when the range modulation is present; the code correlation process associated with ambiguity resolution; and the tracking of the 320-KHz clock signal from which the range measurement is made. In addition, the satellite ephemeris data is also transmitted over the same channel when the ranging signal is not transmitted, i. e., a time-division multiplexing process is used. The total time required for the transmission of the data and ranging signals is about 1. 5 seconds with the satellite transmitter power level of 50 watts given in Table 5-6. Only one of three or four visible satellites will transmit at one time to avoid interference problems. Therefore, the average transmitted power for one satellite will be less than half of the peak power. The exact amount of average power depends on the satellite constellation. The details of the link design are given in Reference 1. Most of the information in Table 19 is taken from Volume 1 of Reference 1. The only changes are associated with new results in the antenna design area and superficial changes to facilitate comparison with other concepts.

The margins listed in Table 19 are available for subnominal conditions such as excessive atmospheric attenuation and fading, reception of the signal from a direction not at the peak of the user antenna pattern, and degraded component performance. It will be seen that the peak transmitted power required for the passive ranging concept is almost an order of magnitude less than that associated with any other concept under consideration here. If larger link margins are required, they may be obtained by either increasing the satellite transmitter power or increasing the acquisition and measurement time interval (which would make it possible to decrease the noise bandwidth at the receiver in the four phases of the measurement process).

The link Equations 30, 31, and 32 show that the path and space losses are inversely proportional to the carrier frequency squared. Lowering the carrier frequency would also lower the transmitted power requirements. Unfortunately, there are no bands that are currently available for utilization by navigation satellites below 1500 MHz until the VHF band is reached. In addition, the range measurement error due to ionospheric refraction error is inversely proportional to the square of the carrier frequency. Reference 24 shows that range measurement errors as large as several miles could occur even when relatively sophisticated calibration procedures are used. The range measurement error is strongly dependent on the relatively unknown nature of the altitude profile of the altitude profile of the electron density in ionosphere and its spatial and temporal correlation structure. Nevertheless, the results in References 1, 24, and 26 plus the dependence of the space loss on carrier frequency indicate that operation in the frequency range between 500 MHz 1000 MHz would yield a reduction in satellite transmitter power requirements by a factor of two to four while the range measurement error

Table 19. Power Budget for Satellite – User Link of Passive Ranging Concept BINOR Code, Carrier Frequency of 1500 MHz

Satellite transmitted power (50 w)	47.0 dbm
Path loss L_{PA} (G_t = 16 db), G_r = 4 db, L_T = -3.8 db)	-172.4 db
Available received power	-125.4 dbm
Noise spectral density (T_N = 743°K)	-169.9 dbm/Hz
Carrier Acquisition Phase (No Modulation)	
Loop noise bandwidth (1650 Hz)	32.2 db
Loop noise power	-137.7 dbm
Loop acquisition threshold SNR	6.0 db
Required carrier power	-131.7 dbm
Available carrier power	-125.4 dbm
Link margin	6.3 db
Carrier Tracking (Modulation Present)	
Loop noise bandwidth (50 Hz)	17.0 db
Loop noise power	-152.9 dbm
Required SNR (due to loop tracking threshold)	10.0 db
Carrier power loss due to modulation (index = 1.2 rad)	8.8 db
Required carrier power	-134.1 dbm
Available carrier power	-125.4 dbm
Margin	8.7 db
Clock Loop Ranging Modulation (320 KHz signal)	
Clock loop noise bandwidth (26 Hz)	14.2 db
Clock loop noise power	-155.7 dbm
Required SNR (for range accuracy of 30 ft)	21.0 db
Ranging signal modulation loss (modulation index = 1.2 rad)	0.6 db
Required carrier power	-134.1 dbm
Available carrier power	-125.4 dbm
Margin	9.7 db
Code Correlations	
Correlation bandwidth (39 cps = correlation time of 0.026 sec)	15.9 db
Correlation noise power	-154.0 dbm
Required correlation SNR (for correct acquisition with probability 0.999)	8.5 db
Correlation loss (0.225)	13.0 db
Ranging signal modulation loss (modulation index = 1.2 rad)	0.6 db
Required carrier power	-131.9 dbm
Available carrier power	-125.4 dbm
Margin	6.5 db
Satellite Data Modulation	
Data channel (bit rate) noise bandwidth (625 cps)	28.0 db
Noise power	-141.9 dbm
Required SNR (for 10^{-4} error probability)	9.5 db
Data channel modulation loss (modulation index = 1.2 rad)	0.6 db
Required carrier power	-131.8 dbm
Available carrier power	-125.4 dbm
Margin	6.4 db

increases by the same amount. Scaling of the results of References 20, 27, and 28 indicate that it should still be possible to obtain user navigation accuracies of the order of 1 nmi in the North Atlantic Ocean area with these operating frequencies. However, no bands in this range are currently allocated for use by navigation satellites.

5.4.3 Active Ranging Concepts

The functional characteristics of the active ranging concept are shown in Figure 66. Early in the study an active ranging concept (described in Reference 37) using conventional pulse modulation for measuring the usersatellite range was examined and found to require excessively large peak satellite transmitter power (of the order of 120 kw) with synchronous satellites. For this kind of active system an even higher transmitted power level (about 165 kw) is required at the user. The details associated with this part of the study are given in Reference 5. However, the primary causes for the large transmitter power requirements are the low user antenna gain of 2 to 4 db and the large slant range associated with synchronous satellites. One way to reduce the transmitter peak power requirements is to reduce the operating frequency. However, the use of the 136- to 150-MHz band leads to the same accuracy problems that are associated with the passive ranging concept. There appear to be no bands in the more desirable 500- to 1000-MHz range that are allocated for use by navigational satellites. Consequently, other alternatives to conventional pulse ranging systems were considered. The capacity requirements that were discussed briedly in Paragraphs 5.1.1 and 5.2.1 imply the need for many tens of thousands of fixes per hour. Thie requirement makes CW tone and coded CW modulation systems (such as BINOR and pseudo-random noise codes) unattractive because of the long acquisition times required at the receiver for reasonable transmitter power levels. This trade is discussed for passive ranging systems in Reference 1 and also applies in general to an active ranging system. The main result is that several seconds are required to acquire the signal with reasonable transmitter power levels before range measurements can be made. Two of the more attractive alternatives appear to be the use of FM chirp modulation and phase coded CW signals in conjunction with a multistage digital matched filter made with microelectronic shift registers. The results of this work are presented in References 4 and 5. A summary of these concepts is presented in the next two subsections.

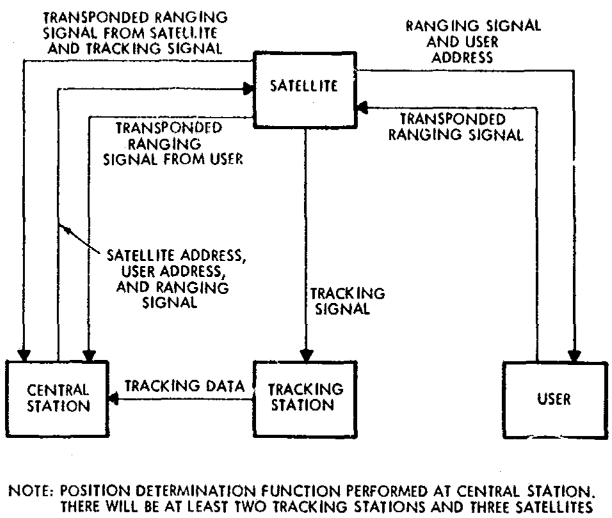


Figure 66. Functional Diagram of Active Ranging Concept

5.4.3.1 Active Ranging with FM Chirp Modulation

FM Chirp signals are generated by varying the carrier frequency of a pulse linearly with time. If the receiver uses a delay line whose delay also varies linearly with frequency, then it is possible to obtain a pulse compression system which "enhances" the signal-to-noise ratio in the receiver. This is a form of matched filter which has been discussed extensively in the literature (e.g., References 17 and 30). One over-simplified explanation of this phenomenon is that the transmitted pulse has its received energy compressed into a smaller time interval. The peak rf power in the original pulse is increased by a factor of $B\tau$ (where B is the change in carrier frequency of the pulse and τ is the transmitted pulse duration). $B\tau$ is called the compression ratio or processing gain.

The use to which the matched filter can be put is obvious in a situation where the chirped pulse is generated in the satellite and detected with the matched filter (or restacked) at the user, viz., an enhancement of the signal-to-noise ratio at the user. However, the use of the matched filter at the user has two disadvantages. The first is in the cost of the user receiver. The cost of a suitable matched filter for ranging with a compression ratio of 100 is estimated to several thousands of dollars in large quantities. This is an appreciable part of the user equipment cost for a cheap system. The second is that mismatches in the time-delay frequency characteristics of the delay lines in the satellite will cause both degradations in the processing gain and the possibility of false alarms due to the generation of additional pulses (time side lobes) at the delay-line output. One way to avoid these problems is to perform the FM chirp pulse generation and detection in the satellite with the same delay line. With this approach, the user cost is reduced since the user equipment will involve only a transponder. Also the use of the same delay line to generate and detect the FM chirped pulse signal will minimize the effects of mismatches that would occur if different delay lines were used. Even if the compressive delay line used for detecting the ranging signals is placed in the satellite, a delay line will be needed in the user transponder to gate on the transmitter after the user address pulses are detected. In addition to the compressive delay line in the user to detect the address signals, it is also necessary to have a delay line to delay the ranging signal until the user transmitter is turned on. The specifications on these delay lines are less stringent than on the compressive delay link used for ranging. Further details are given in Section 5.6 of this report and Reference 5. However, these considerations do not affect the navigation link power budget to an appreciable extent.

Now the effect of noise in the user's input stage will be examined. If the received signal at the user is amplified linearly (without the presence of either of the threshold effects that would occur if the chirped signal were detected or limited), then the noise present at the user's input will be transmitted along with the signal. If P_{tu} is the total transmitted power output from the user, P_{su} the component of the user transmitted output due to the signal, P_{Nu} the component of the transmitter output due to the noise, and SNR_u the signal-to-noise ration in the user, then since the signal and noise are uncorrelated,

$$P_{tu} = P_{su} + P_{Nu} = P_{su} \left[1 + \frac{1}{SNR_u}\right] \tag{34}$$

If SNR_{s1} is equal to the signal-to-noise ratio at the satellite's rf input, SNR_{s2} is equal to the signal-to-noise ratio at the output of the matched filter, ρ_p is the processing gain associated with the matched filter, and P_{Ns} is the noise power generated at the satellite input stage, then

$$SNR_{s2} = \rho_p \, SNR_{s1} = \frac{\rho_p \, L_{PA} \, P_{su}}{P_{Ns} + L_{PA} \, P_{Nu}}$$

$$= \frac{\rho_p \, L_{PA} \, P_{su}}{P_{Ns} + (L_{PA} \, P_{su}/SNR_u)} \tag{35}$$

Now define $SNR_{s0} = (L_{PA} \, P_{su})/P_{Ns}$. Then SNR_{s0} is the signal-to-noise ratio that would exist at the satellite if no noise were transmitted from the user ($P_{Nu} = 0$). Then equation (5-6) becomes

$$SNR_{s2} = \frac{\rho_p \, SNR_{s0}}{1 + \dfrac{SNR_{s0}}{SNR_u}} = \frac{\rho_p \, SNR_{s0} \, SNR_u}{SNR_u + SNR_{s0}} \tag{36}$$

Therefore, for $\rho_p >> 1$, one can obtain a suitable value of SNR_{s2} with much lower values of SNR_{s0} and SNR_u then would be the case without the use of the matched filter in the satellite ($\rho_p = 1$). Therefore, lower peak transmitter output power levels are required with the matched filter. As an example, if $SNR_{s0} = SNR_u = 0$ db and $\rho_p = 100$, then $SNR_{s2} = 50 = 17$ db.

The preceding analysis assumes that the transponder is linear, i.e., if signal power at the user's received input changes by a factor of k db, then transmitted signal power from the user will also change by k db. For the conditions in the ERC Navigation/Traffic Control Satellite Mission Study, the signal dynamic range at the receiver input should be about 10 db and it appears reasonable to assume that the transponder power gain characteristics are linear. Therefore, the preceding analysis can be used to examine tradeoffs in the power budget for the navigation link. However, if limiting and automatic gain control are used in the user transponder, then the relationships between the signal-to-noise ratios at the satellite input, the user input, the transmitted power from the user, and the path loss become more involved and Equation 36 will no longer be valid. For example, the signal-to-noise ratio at the output of a nonlinear receiver will not be equal to the signal-to-noise ratio at the input. This assumption is needed to derive Equation 36 since SNR_u is assumed to be the signal-to-noise ratio at both the user receiver input and the user transmitter output and also to interpret SNR_{so} as the signal-to-noise ratio that would exist at the satellite $P_{no} = 0$. (It is also necessary to assume that the dominant source of noise in the user equipment is at the input stage which should create no major conflicts with reality.)

In some cases, the effects of limiting can be incorporated into the preceding analysis. One general way involves expressing the signal-to-noise ratio at the output of a receiver as a function of the signal-to-noise ratio at the input to the receiver. Another case involves the situation where the total transmitter output power P_{tu} is fixed as a result of limiting. In this case, it is convenient to rewrite Equation 34 as

$$P_{su} = P_{tu} \left[1 + \frac{1}{SNR'_u} \right]^{-1} \tag{37}$$

SNR'_u is the signal-to-noise ratio at the transmitter output which may or may not be equal to the signal-to-noise ratio at the input depending on the limiting characteristics. Then Equation 35 yields

$$SNR_{s2} = \rho_p \, SNR_{s1} = \frac{\rho_p \, L_{PA} \, P_{tu} \left[1 + \frac{1}{SNR'_u} \right]^{-1}}{P_{NS} + L_{PA} \, P_{tu} (SNR'_u + 1)^{-1}} \tag{38}$$

$$= \frac{\rho_p \, SNR'_{s0} \, SNR'_u}{1 + SNR'_u + SNR'_{s0}}$$

SNR'_{s0} is interpreted as the signal-to-noise ratio that would exist at the satellite input if all the available transmitted power, P_{tu}, were signal power. This differs from the entity SNR_{s0} used in Equation 35 which is the signal-to-noise ratio that would exist at the satellite input if only the signal component of the transmitter output power was transmitted. Another similar approach to this problem is presented in Appendix A of Reference 6.

In any case, the analysis of active ranging navigation linke is a complex problem which involves many variables.

For the satellite-user downlink of the FM chirp pulse compression active ranging concept, the sky temperature T_{sky} is the same as it was for the active ranging concept ($T_{sky} = 80^{o}K$). The receiver noise figure, F, is taken to be 3.5 db for this concept which is based on a more optimistic forecast of capabilities in the area of low noise receivers than was the case for the passive ranging concept and the fact that relatively high peak and average satellite transmitter power requirements (that are present even with the use of pulse compression) make it desirable to spend a reasonable amount of effort to minimize the noise in the user receiver's front end. The rf losses, L_{rf}, at the user's front end are taken to be 2 db (0.8 db in cable losses and 1.2 db in user diplexer losses). The use of Equation (5-4) yields an effective noise temperature T_N of $518^{o}K$. If a receiver with F = 5 db (which is the noise figure used in the passive ranging power budget) is specified, then T_N equals $788^{o}K$ (for $L_{rf} = 2$ db) and the signal-to-noise ratio at the user will be degraded by 1.9 db.

At the receiver in the satellite, the antenna temperature (which is analogous to the user antenna sky temperature T_{sky}) will be $290^{o}K$ since the satellite's antenna will be designed to cover the earth and the earth's temperature is approximately $290^{o}K$. With the rf circuit input losses, L_{rf}, taken at 1 db (due to the diplexer) and a satellite receiver noise figure (F) of 5.3 db yields a noise temperature $T_N = 985^{o}K$ for the uplink. This represents a conservative assumption for the satellite receiver.

The losses in the satellite-to-user link are

Satellite diplexer	=	-1.0 db
Atmospheric attenuation	=	-1.0 db
Polarization (user)	=	-1.0 db
User diplexer	=	-1.2 db
User cable	=	-0.8 db
Total losses = L_T	=	-5 db

The space losses L_{SP} are -188.6 db and (with a satellite antenna gain of 16 db and a user antenna gain of 4 db) the path losses L_{PA} are -173.6 db for the satellite-to-user downlink. The same assumptions are made for the user-to-satellite uplink. The power budget for these two links is given in Table 20. This is based on the design in Reference 5. The processing gain is 100, the transmitted pulse duration is 45 microseconds, the compressed pulse duration is 0.45 microseconds, the noise bandwidth is 2.2 MHz, and the carrier frequency chirp is 2.2 MHz. Further details are given in Reference 5 and in Section 6 of this report.

The choice of -0.6 db as the design signal-to-noise ratio at the user transmitter output was made as a result of a trade between peak user transmitter power and peak satellite transmitter power which is described in Reference 5. The results of this study which are given in Figure 7 of Reference 5 are reproduced here in Figure 67.

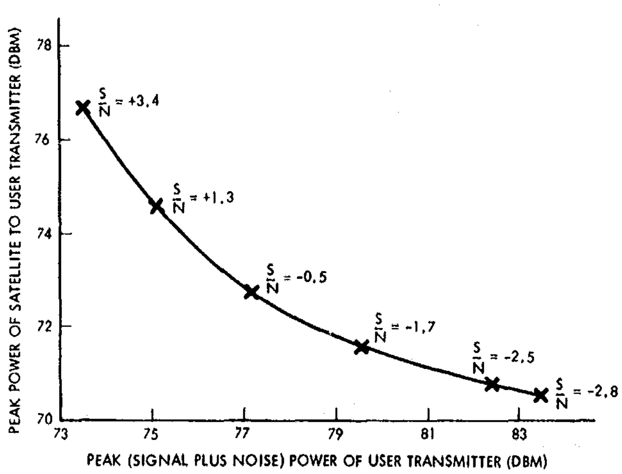


Figure 67. User and Satellite—User Transmitter Peak Power Versus User S/N (Chirped), Active Pulse Ranging NavSat

The curve in Figure 67 and the results in the power budget all indicate that peak transmitted signal power levels of the order of tons of kilowatts will be required at the user and the satellite. The additional user transmitter power required to transmit the noise will be of the same order of magnitude. Furthermore, the average power required in the satellite is shown in Reference 5 to be about 240 W. This is considerably larger than a desirable level. One way to reduce both peak and average power requirements in the satellite and the user would be to increase the processing gain above 100. It appears questionable that this can be done with delay-lines in an FM chirp system based in a satellite so that an operating life of the order of several years can be obtained. In particular, component degradation presents a source of concern. It would also be possible to decrease the satellite and user transmitter power requirements by using a lower frequency. However, the same problems of lack of availability of frequencies in the band between 500 and 1000 MHz and poor accuracy at VHF that were discussed in connection with the passive ranging concept in Paragraph 5.4.2 also apply here. Therefore, an alternate mechanization of the active ranging concept was examined in the ERC Navigation/Traffic Control Satellite Mission Study.

Table 20. Power Budget for FM Chirp Pulse Compression Active Ranging Concept

Satellite transmitted (signal) power (18.6 KW)	72.7 dbm
Path loss or downlink (L_{PA})	-173.6 db
Receiver noise spectral density (T_N = 518°K)	-171.5 dbm/Hz
Noise bandwidth at user (2.2 MHz)	63.4 db
Available user received signal power	-100.9 dbm
Available user received noise power	-108.1 dbm
Nominal user SNR (no additional losses)	7.2 db
Design user SNR (chosen from consideration of Figure 67)	-0.6 db
Design margin in downlink	7.8 db
Design total user transmitted power (signal + noise) (52.5 kw)	77.2 dbm
Design user transmitted signal power (24.5 kw)	73.9 dbm
Design user transmitted noise power (28 kw)	74.5 dbm
Path loss on uplink (L_{PA})	-173.6 db
Design received signal power at satellite	-99.7 dbm
Design received noise power at satellite	-99.1 dbm
Noise spectral density at satellite input (T_N = 985°K)	-168.7 dbm/Hz
Noise bandwidth at satellite (2.2 MHz)	63.4 db
Noise power from satellite input stages	-105.3 dbm
Design received signal power to satellite input stage noise power ratio (SNR_{s0} = 3.5 = 5.4 db)	5.4 db
Total available design noise power at satellite in input stage	-98.2 dbm
Design SNR at satellite input	-1.5 db
Processing gain (100)	20. db
Design ranging SNR (SNR_2)	18.5 db
Desired ranging SNR	15.0 db
Uplink SNR_2 design margin for 15 db ranging SNR - (from Equation 5-7)	
a) Downlink margin of 7.8 db (required SNR_u = -0.6 db)	3.8 db
b) Downlink margin of 3.6 db (required SNR_u = 3.6 db)	6.4 db
c) Downlink margin of 0 db (required SNR_u = 7.8 db)	8.4 db

5.4.3.2 Active Ranging Using a Digital Matched Filter or Phase Coded Pulse Compression

In recent years, there have been some notable improvements in large scale integration microelectronics. As a result of these improvements, it becomes feasible to build shift registers that have of the order of 2000 stages and a bit rate of the order of several MHz with microelectronic techniques. These shift registers can serve the same function as tapped delay lines in a phase coded matched filter (Reference 17). In a phase coded pulse compression system, the number of stages (taps) in a tapped delay line is approximately equal to the processing gain (see Reference 17). With conventional analog delay lines, a processing gain of the order of 100 is feasible. This limitation is due to anomalies and instabilities in the electrical and mechanical characteristics of the components of the delay line. When the microelectronic shift registers with several thousand stages are used for delay lines and the appropriate taps are used, then high gain digital matched filters can be constructed. The characteristics of some mechanizations of such filters are described in References 4 and 31. A functional block diagram of one mechanization of a noncoherent digital matched filter is shown below in Figure 68. The

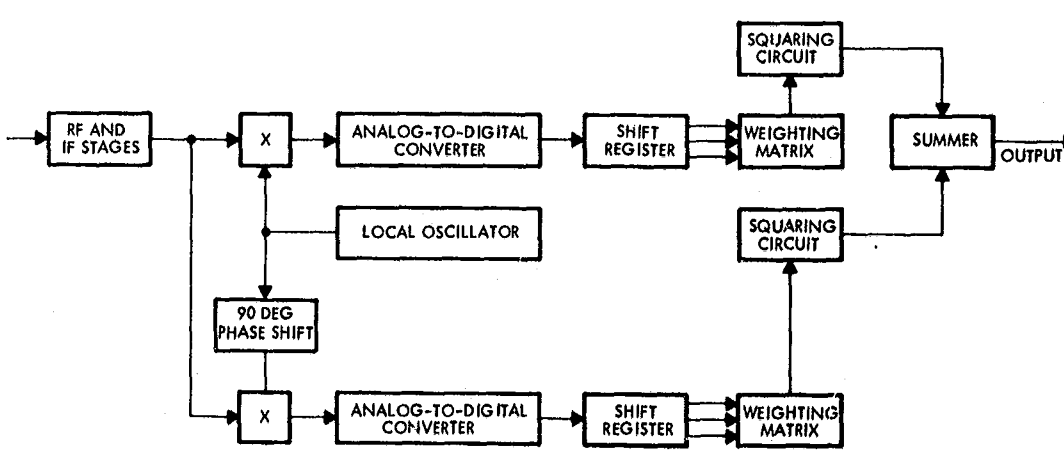


Figure 68. Noncoherent Digital Matched Filter for Phase Coded Pulse Compression

coded input signal is in the form of a bi-phase modulated signal where one of the two possible phases represents a binary one the other a zero. The two shift registers and squaring network are used to avoid the requirement for coherent detection. The details of the operation of this filter and more details concerning mechanization are given in References 4 and 31. A matched filter with a processing gain of 2000 in the satellite of an active ranging system can be used in several ways. One thing that could be done would be to reduce the satellite transmitter power by a factor of the order of about 20 to a level of 900 watts peak and 50 watts average. Another approach to the use of such a digital matched filter in an active ranging system is to use the digital matched filter in the ground station. This approach has the advantage of placing this admittedly complex piece of equipment in a position where it can be serviced and/or replaced without a requirement to launch another satellite. Furthermore, the physical environment of the digital matched filter is more easily controlled in a ground station. This makes it easier to control the effects of factors such as temperature sensitivity. This approach to an active ranging concept will be examined in more detail in the rest of this subsection.

The satellite and user navigation link equipment will consist of linear transponders for this implementation of the active ranging concept. The same assumption that was made in the previous subsection concerning the dynamic range of the input signals (i.e., it is of the order of 10 lb) is also made here. Since the digital matched filter is located at the ground station, the ranging signal is detected there. The satellites and the users are addressed by a special code that is broadcast before the ranging signal in each navigation message. Noise power will be transmitted from the user and the satellite due to noise in the input circuits. The same technique that was used to analyze the effect of transmitted noise power in the previous subsection with an FM chirp system will now be used for the digital phase coded system. Let P_{ts} be the total power transmitted from the satellite (to the ground station), let P_{ns} be the noise transmitted from the satellite (to the ground station), let P_{ss} be the signal transmitted from the satellite (to the ground station), let ρ_p be the processing gain associated with the digital matched filter, let SNR_{G1} be the signal-to-noise ratio at the matched filter input, let SNR_{G2} be the signal-to-noise ratio at the matched filter output, let L_{PAG} be the path loss on the satellite-to-ground station downlink, and let SNR_{GO} be the signal-to-noise ratio at matched filter input for the case where no noise is transmitted from the satellite. Then the same approach that was used in Section 4.3.1 yields

$$P_{ts} = P_{ss} + P_{Ns} = P_{ss}\left(1 + \frac{1}{SNR_s}\right) \tag{39}$$

$$SNR_{G1} = \frac{L_{PAG}\, P_{ss}}{N_G + L_{PAG}\, P_{Ns}} = \frac{L_{PAG}\, P_{ss}}{N_G + (L_{PAG}\, P_{ss}/SNR_s)} \tag{40}$$

$$= \frac{SNR_{GO}}{1 + (SNR_{GO}/SNR_s)}$$

If the signal-to-noise ratio in the ground station-satellite uplink is greater than 7.3 db at the satellite (or reasonably large so that the noise transmitted from the satellite is negligible relative to the user noise), then Equation (5-7) with $\rho_p = 1$ gives SNR_s and Equation 40 yields

$$SNR_{G2} = \rho_{p_2}\, SNR_{G1} = \frac{\rho_{p_2}\, SNR_{GO}\, SNR_{s0}\, SNR_u}{SNR_{s0}\, SNR_u + SNR_{GO}(SNR_u + SNR_{s0})} \tag{41}$$

Equation 41 demonstrates the advantage of a large value of ρ_p in that relatively small satellite transmitted powers in the satellite-user downlink (which imply small values of SNR_{GO}, SNR_{s0}, and SNR_u) can yield a reasonable value of SNR_{G2} (at the detection point) if ρ_p is large enough. The same comments and analytical approach associated with the discussion and derivation of the effects of nonlinear characteristics in the transponder in Equations 38 and 39 can be applied here.

A typical power budget for a digital matched filter is presented in Table 21. The satellite-user downlink, user-satellite uplink, and satellite-ground station downlinks are of primary concern. The ground station-satellite uplink is not a major problem in the design of this or other active ranging concepts because a large ground antenna and a powerful ground transmitter can be combined to provide a high signal-to-noise ratio at the satellite input. The path losses and noise temperatures in the user and satellite are assumed to be the same as those associated with the FM chirp system. For the satellite-ground station link, the ground station antenna gain is assumed to be 41 db and the sky temperature $T_{sky} = 50^{o}K$. With a ground station noise figure of 1.36 db and a set of rf losses (L_{rf}) at the ground station equal to 2 db, Equation 40 yields $T_N = 250^{o}K$ as the noise temperature at the ground station receiver input. The power budget indicates that ground station noise is not a major factor in system performance (see discussion below) so the ground station noise temperature is not critical.

Table 21. Power Budget for Phase Coded Digital Matched Filter Active Ranging System

Satellite transmitter power (3.1 kw)	64.9 dbm
Path loss (L_{PA})	-173.6 db
Receiver noise spectral density ($T_N = 518^{o}K$)	-171.5 db/Hz
User ranging noise bandwidth (2.2 MHz)	63.4 db
Available user noise power	-108.1 dbm
Available user received ranging signal power	-108.7 dbm
Nominal user ranging SNR (SNR_u)	-0.6 db
User noise power during carrier acquisition*	-128.5 dbm
Available user carrier signal power*	-108.7 dbm
Carrier acquisition SNR*	19.8 db
Total user transmitter power = P_t (31 kw)	74.9 dbm
User transmitted signal power = $P_t \, SNR_u (1 + SNR_u)^{-1}$ = (14 kw)	71.5 dbm
User transmitted noise power = $P_t (1 + SNR_u)^{-1}$ = (17 kw)	72.3 dbm
Path loss (L_{PA})	-173.6 db

*Carrier acquisition to detect user address signals in ranging message.

Table 21. Power Budget for Phase Coded Digital Matched Filter Active Ranging System (Continued)

Received signal power at satellite	-102.1 dbm
Received noise power at satellite	-101.3 dbm
Noise spectral density at satellite input ($T_N = 985^oK$)	-169.3 dbm/Hz
Noise bandwidth at satellite (2.2 MHz)	63.4 db
Noise power generated at receiver input stages	-105.9 dbm
Total noise power available at satellite input	-100.1 dbm
Satellite SNR (SNR_s)	-2.0 db
Ideal satellite SNR (SNR_{s0}) with no-noise transmitted by user	3.8 db
Satellite transmitted signal power (56 W)	47.5 dbm
Satellite transmitted noise power (94 W)	49.7 dbm
Total satellite transmitted power (150 W)	51.8 dbm
Space loss (L_{SP})	-188.6 db
Satellite antenna gain	16. db
Ground station antenna gain	41. db
Line losses (L_T)	5. db
Path loss (L_{PA})	-136.6 db
Received signal power at ground station	-89.1 dbm
Received noise power at ground station	-86.9 dbm
Equivalent noise spectral density in ground station receiver ($T_N = 250^oK$)	-174.6 dbm/Hz
Noise bandwidth at ground station receiver (2.2 MHz)	63.4 db
Equivalent noise power in ground station receiver	-111.2 dbm
Total noise power at ground station input	-86.9 dbm
Ideal ground station SNR (SNR_{GO})	22.1 db

Table 21. Power Budget for Phase Coded Digital Matched Filter Active Ranging System (Continued)

Input ground station SNR	-2.2 db
Processing gain (2000)	33. db
Available ranging SNR	+30.8 db
Required ranging SNR (10^{-4} false alarm prob.)	18. db
Margin	12.8 db

There are several interesting characteristics associated with the power budget for the digital matched filter active ranging system presented in Table 21. These characteristics are also present to a lesser extent in the power budget for the FM chirp active ranging system discussed in Section 5.4.3.1. First, these concepts both have repeaters or transponders where the received signal plus the noise in the input stage is amplified and retransmitted by a linear power amplifier. This condition results in inefficient use of transmitter output power since a considerable part of the output power is devoted to the transmission of unwanted noise as well as the signal. Furthermore, the weak part of the link (in terms of signal-to-noise ratio) tends to determine the signal-to-noise ratio at the input stage before detection by the matched filter. Thus, the use of a matched filter in the satellite for the FM chirp implementation can be considered to imply a requirement for high peak transmitter power from the user (due to the fact that the amplified noise as well as the signal from the user input stage is transmitted back to the satellite) instead of a requirement for either a matched filter at the user (to reconstitute the dispersed pulse) or a high peak transmitter power requirement at the satellite. Likewise, the use of the digital matched filter at the ground station implies a requirement for a relatively high peak transmitter power output at the user due to the transmission of noise power from the user's input stage. The peak power required from the user's transmitter could be reduced by increasing the peak power from the satellite in the satellite-user downlink or using a digital matched filter at the user. Thus, in both cases a high power transmitter at the user is chosen instead of a complex user receiver with a matched filter. Also, in both cases, it is undesirable to increase the satellite peak power output. Note that with the power budget in Table 21, the noise in the input stages of the satellite receiver and the ground station receiver does not contribute appreciably to the noise power in the ground station receiver.

The message duration (for one navigation transmission) of the digital matched filter implementation of the active ranging concept is 9 milliseconds. One message is transmitted approximately every 360 milliseconds. Therefore, the duty cycle in the satellite will be approximately 1025 and the average rf power required will be about 80 watts. If a 33 percent efficiency is assumed in converting DC power into rf power, then about 240 watts of DC power will be required in the satellite. This is a relatively large power requirement, and it indicates that further studies to define more exactly the processing gains available with a digital matched filter and a more thorough optimization of the power budget in Table 21, are needed if the active ranging concept is to be developed further. A thorough optimization of the power budget for the digital matched filter implementation was not possible within the scope of the Navigation/Traffic Control Satellite Mission Study. In addition, the effects of the methods of compensating for the effects of Doppler shifts in the digital matched filter need further examination although a preliminary study of this problem was made and is described in Reference 4 where several possible solutions to this problem are discussed.

5.4.4 Active Range and Angle Measuring Interferometer Concept

The active range and angle measuring concept was studies by Westinghouse and is described in detail in Reference 6. A functional block diagram of this concept is shown in Figure 62. It features the capability to determine the user's position with a single satellite. The single satellite transmits an FM chirped ranging signal and addressing pulses to the user. The user retransmits the ranging signal and a single CW pulse. The satellite has a filter matched to a chirped signal to detect the ranging pulse and a receiving interferometer which measures the angular orientation of the line of sight using interferometric techniques. The characteristics of the power budget for the ranging link are similar to those in Paragraph 5.4.3.1.

The characteristics of the power budget for the angle measuring link were not investigated in detail in this study. The detailed power budget will depend on the interferometer design in the satellite. Several possibilities are presented in Reference 6. It is easy to show that a large noise bandwidth (relative to the noise bandwidth of the passive interferometer) that results from the requirement to make a phase measurement in 10 milliseconds can result in a large user peak transmitter power requirement. Another difference between the passive and active interferometer power budgets is due to the reduced sensitivity to angle measurement errors when range information is available. The similarity in the ranging links is adequate for the examination of comparisons among different concepts (but not for detailed system design considerations). Hence, a separate analysis of the power budget for this system is not required for making the necessary comparisons among the different navigation concepts.

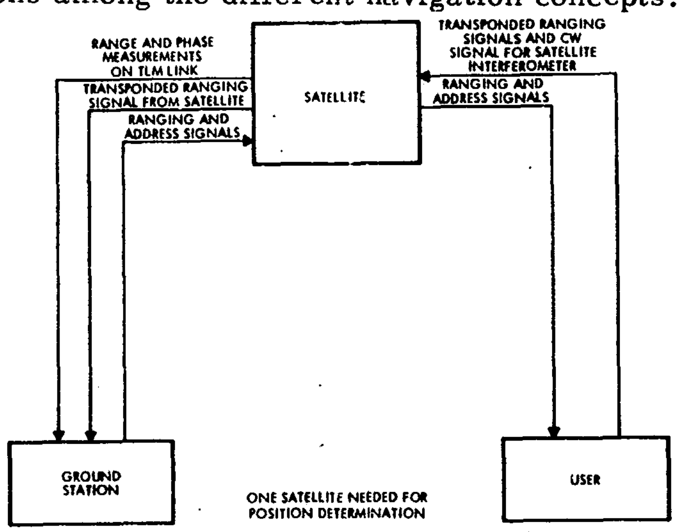


Figure 69. Functional Diagram of Active Angle and Ranging Concept

5.4.5 Passive Interferometer

The starting point for the design of a passive interferometer concept involves a tradeoff between electrical phase measurement accuracy, attitude control system design problems, space losses, and position determination accuracy requirements. The functional diagram of this concept is given in Figure 70. The space losses are given in Equation 31 and increase as the square of the carrier frequency. The navigation accuracy is related to the electrical phase measurement accuracy by Equation 30 which can be rewritten as

$$R\delta\theta \csc E = \delta P = \frac{\delta\phi \csc E}{2\pi n \sin \theta} R \tag{42}$$

where

n = number of electrical wavelengths of baseline = D/λ

R = slant range

δP = navigation error

E = elevation angle of line of sight at user

θ = angle between line of sight and baseline

$\delta\phi$ = electrical phase measurement error

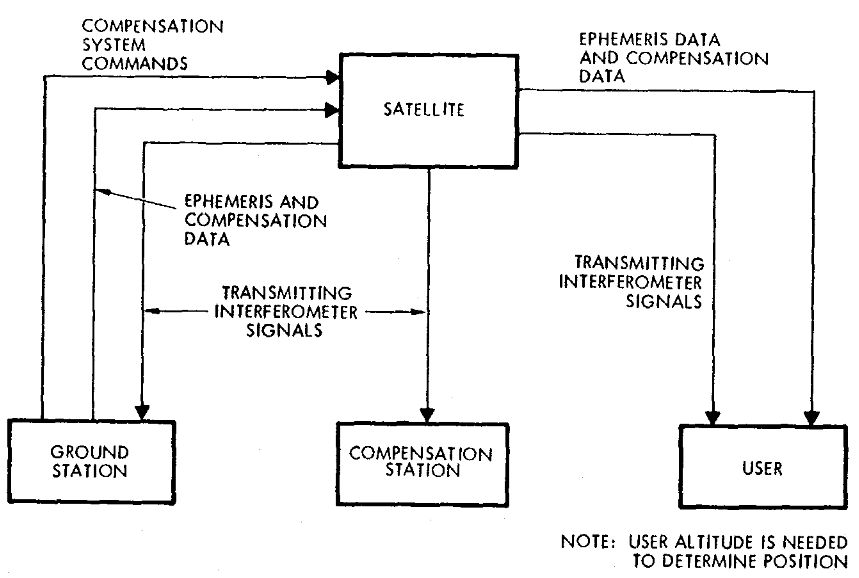


Figure 70. Functional Diagram of Passive Interferometer Concept

Reference 32 indicates that a satellite interferometer with booms whose length is 75 feet (about a 150-feet long baseline, D) will result in an unstable control system with present technology while a preliminary examination of 10-feet booms indicate that it may be possible to design a reasonable attitude control system for this case. Therefore, a boom length of the order of 10 feet and a value of D of 20 feet will be assumed in this discussion. (D will include the boom length plus the appropriate satellite structure dimensions.) While it might prove feasible to increase D to a value greater than 20 feet but less than 150 feet, this will make a critical attitude control system design problem more difficult. Hence, it seems reasonable to assume D = 20 feet in the subsequent discussion. For $\delta P \cong 1$ nmi, and R = 22,700 nmi, $\delta\theta \cong 8$ microradians for a line-of-sight elevation angle 10 degrees at the user. For larger elevation angles, the allowable angle measurement error $\delta\theta$ increases (to 50 microradians at an elevation angle of 90 degrees). Consequently, the same phase measurement accuracy and baseline length will yield improved accuracy at greater elevation angles. Since $\sin\theta \sim 1$ for synchronous satellites,

$$\delta\phi = (2\pi n) \times (8 \times 10^{-6}) = 16 n\pi \times 10^{-6} \tag{43}$$

If an electrical phase measurement accuracy* (1 sigma) of 0.02 radians is assumed, then Equation 43 becomes

$$n = \frac{2 \times 10^{-2}}{16\pi \times 10^{-6}} = 400 = \frac{D}{\lambda} \tag{44}$$

With D = 20 feet, Equation 44 yields $\lambda = 0.05$ feet. The carrier frequency for this wavelength is 19.6 GHz. In view of the fact that the requirement for 1-nmi accuracy for $E = 10^{\circ}$ and the phase measurement accuracy of 0.02 rad* are not firmly established and the fact that space

*Actually, there are two sources of phase measurement errors, i.e., thermal noise and biases of various kinds in the receiver. Each of these error sources is assumed to be independent and to have a standard deviation of 0.02 rad phase measurement error in the error budget in Section 5. Here the interferometer boom is sized so that the above accuracy will be met for both sources. The total standard deviation of the phase measurement due to these two error sources is 0.028 rad.

losses increase as the square of the carrier frequency, it is reasonable to compromise a bit. Therefore, it will be assumed that the carrier frequency is 9.7 GHz (which will give a 1 one sigma navigation error about 2 nmi under the above conditions with $E = 10^{\circ}$ and 0.36 nmi with $E = 90^{\circ}$). For this set of compromise conditions, $n = D/\lambda = 200$ (with a phase measurement accuracy of 0.02 rad*).

Several implementations of a passive interferometer system are possible. Some of these are described in Reference 35. However, these different implementations do not differ to a great extent as far as trades between accuracy, transmitted power, and baseline length are concerned. The differences are primarily in the area of electronic mechanization. Consequently, the switched transmitting interferometer will be examined here. The switched transmitting interferometer uses an rf transmitter in the satellite whose output is periodically and frequently switched from one interferometer antenna to the others. For the passive interferometer navigation system, two antennas will be used with each baseline for a total of four antennas in the satellite. For purposes of establishing a power budget, it will be assumed that two separate phase measurements are made using a local reference to determine the phase difference between signals from opposite ends of a baseline. The variance of the phase difference will be twice the variance of one phase measurement. Then, if S/N is the video signal-to-noise ratio at the detection point, the accuracy** for one pair of phase measurements (which are made by separate measurements using a reference on the use of of the phase of the signals transmitted from each end of the baseline) is given by

$$\sigma_{\phi}^{2} = E\,(\delta\phi)^{2} = \frac{1}{(S/N)} = \frac{1}{(S/N_{o}\,B_{n})} \tag{45}$$

---

*Actually, there are two sources of phase measurement errors, i.e., thermal noise and biases of various kinds in the receiver. Each of these error sources is assumed to be independent and to have a standard deviation of 0.02 rad phase measurement error in the error budger in Section 5. Here the interferometer boom is sized so that the above accuracy will be met for both sources. The total standard deviation of the phase measurement due to these two error sources is 0.028 rad.

**This result is valid for high signal-to noise ratios. A more general result is given in Reference 36.

where S/N_o is the total signal power to noise power spectral density ratio and B_n is the noise bandwidth of the receiver. Thus, for $\sigma\phi = 0.02$ radians, which assumes that the phase measurement error discussed previously is composed of equal components due to thermal noise and receiver biases, $S/N = 10,000 = 40$ db. The power budget for a system with a 9.6 GHz carrier frequency is shown in Table 22. The noise temperature T_N is derived from Equation 33 and turns out to be $743^{\circ}K$. Here the user receiver noise figure, F, is assumed to be 5 db and the rf losses, L_{rf}, are assumed to be 0.8 db. The losses in the link, L_T (see Equations 30 and 32, are 3.8 db which are derived as follows:

User circuit and cable losses	0.8 db
Polarization and antenna losses	1.0 db
Atmospheric attenuation	2.0 db
Total losses, L_T	3.8 db

There are no differences for losses due to satellite and user diplexers since there elements are not present in a passive interferometer satellite-to-user-navigation link. As before, the user antenna gain is assumed to be 4 db and the satellite gain, 16 db. The sky noise temperature, T_{sky}, is assumed to be $80^{\circ}K$ with $30^{\circ}K$ assumed to be due to radiation from the ground into the user antenna and $50^{\circ}K$ due to atmospheric attenuation. At 9.6 GHz (X-band), the contributions due to galactic noise are assumed to be negligible. The receiver noise bandwidth is assumed to be 0.25 Hz. For a second order filter on the phase tracking loop output, this leads to a navigation error due to dynamic effects (in the absence of noise) of the order of 0.5-n mi for a speed of 3000 ft/sec. Here it is assumed that a phase measurement of the difference between the signals is made very rapidly relative to the time constants of the above filter.

Table 22 indicates that 330 watts are required for two channels in a passive interferometer if time multiplexing is used among the four antennas associated with the two channels. The average power could be decreased considerably below this level by transmitting in bursts to

Table 22. Power Budget for Passive Interferometer Concept

Peak transmitted power (330W)	55.2 dbm
Space loss (9.7 GHz)	-204.3 db
Path loss ($L_{PA} = L_{SP} G_t G_r L_T$) (transmitter terminals to receiver terminal	-188.1 db
Receiver noise spectral density ($TN = 743^{o}K$)	-169.9 dbm/HZ
Receiver noise bandwidth (0.25 Hz)	-6. db
Equivalent receiver noise power	-175.9 dbm
Received signal power	-132.9 dbm
Signal-to-noise ratio	43. db
Required signal-to-noise ratio (1.2^{o} phase measurement due to noise)	40. db
Link margin	3. db

Note: Transmitted power requirements can be reduced appreciably by using lower carrier frequency (which will result in degraded accuracy).

obtain a duty cycle of the order of 20 to 50 percent. The space loss Equation 31 shows that the required transmitted power will increase as the square of the carrier frequence while Equation 42 indicates that the navigation error due to phase measurement errors will decrease with carrier frequency. The power budget in Table 22 pertains to a 2.8 nmi 1 sigma accuracy due to thermal noise and receiver bias* at an elevation angle of 10 degrees (or a 0.48 nmi 1 sigma accuracy at an elevation angle of 90 degrees) with a 9.7 GHz carrier frequency. If the 1 sigma error due to thermal noise and receiver bias were allowed to increase to 6 nmi at a 10-degree elevation angle and 1.08 nmi at a 90-degree elevation angle, then the carrier frequency could be lowered to 3.2 GHz, and the required peak power would be 330 watts/9 or 37 watts.

*This considers receiver bias and thermal noise as independent error sources and allots a 2 nmi standard deviation to each of them.

Clearly, a useful compromise between accuracy and transmitted power is possible. However, this compromise must also consider the effects of navigation errors due to attitude control system imperfection and boom bending. These effects are discussed in Section 5.4 of this report and play an important factor in the evaluation of the passive interferometer concept. If the effects of boom bending on both accuracy and control system stability can be controlled to a reasonable level with boom lengths greater than 10 feet, then this will help the trade between transmitter power and accuracy (since it will allow an increase in $n = D/\lambda$ by increasing D rather than decreasing λ). Therefore, the attitude control system design is a part of this trade.

5.4.6 Spinning Fan Beam Concept

The spinning fan beam concept uses the passage times of two orthogonal fan beam antenna patterns over the user to determine the angular orientation of the line of sight between the satellite and the user. A reference signal must also be transmitted to enable the user to determine when the satellite is oriented in a reference position with the antenna patterns pointed in a reference direction. In this section, the fan beam channels will be considered since this channel is the source of a major feasibility problem in the fan beam concept. A functional diagram for the fan beam concept is shown in Figure 71. Further details of the fan beam concept are given in References 8 and 14.

Reference 38 shows that the angular measurement accuracy is approximately related to the crossing time measurement accuracy by

$$\sigma_{\phi} = \frac{\omega_s \sigma_T}{\sqrt{2}} \tag{46}$$

where σ_T is the standard deviation of the crossing time measurement, ω_s the spin rate of the satellite, and σ_{ϕ} the standard deviation for the angular measurement. For the case where (a) the errors in the two fan beam crossing time measurements are independent, (b) the two fan beams are spatially orthogonal, and (c) the angle between the spin axis and the line of sight equals 90 degrees, Equation 36 is an exact relation for angular measurement errors in two orthogonal directions. Conditions (a) and (b) are valid for a preliminary analysis. The angular measurement error

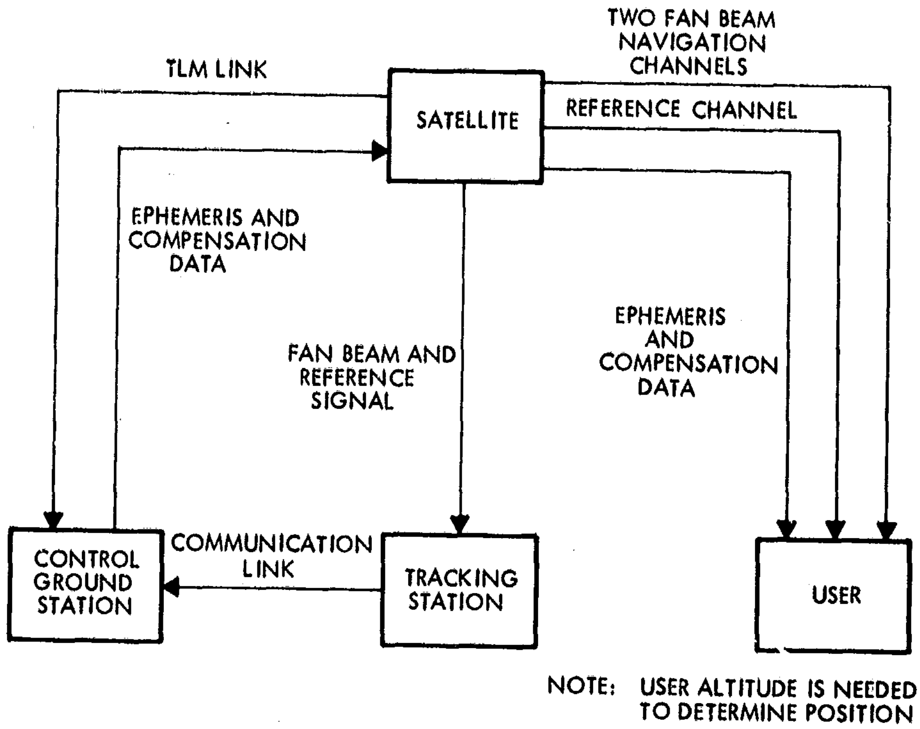


Figure 71. Functional Diagram of Spinning Fan Beam Concept

can be shown to decrease as the sine squared of the angle between the line of sight and the spin axis. Since this angle will never be smaller than 80 degrees or greater than 100 degrees, the effect of this variation on the present analysis is negligible. A nominal value of ω_s is shown to be 10 radians per second in Reference 14 due to the results of a trade between antenna boom length, antenna beam width, stresses in the boom that result from spinning, carrier frequency, and spin axis stability. Values of ω_s of the order of 20 radians per second (3.2 revolutions per second) are desirable from the point of view of stability. Ten radians per second is claimed to be a reasonable compromise.

It is well known (see Reference 17) that if an optimum estimator is used for determining the time of arrival of the phase, then

$$\sigma_\epsilon = \frac{1}{\beta(2E/N_o)^{1/2}} \tag{47}$$

where is the effective bandwidth (or radius of gyration of the signal's amplitude spectrum about the origin), E is the energy in the signal, and N_o is the noise spectral density at the detection point. After the pulse generated by the fan beam antenna pattern has been passed through several stages of IF amplification, it is reasonable (for the purpose of establishing a relationship between transmitter power and accuracy) to assume that the signal has a Gaussian waveform

$$s(t) = S(O)\, e^{-a^2 t^2/2} \tag{48}$$

For this type of signal

$$\int_{-a}^{a} |s(f)|^2 df = E = \int_{-\infty}^{\infty} s(t)^2\, dt = \frac{\sqrt{\pi}}{a}\, s(O)^2 \tag{49}$$

$$\beta^2 = \frac{1}{E} \int_{-\infty}^{\infty} (2\pi f)^2\, |S(f)|^2\, df$$

$$\beta = \left[\frac{1}{E} \int_{-\infty}^{\infty} \left(\frac{ds}{dt}\right)^2 dt\right]^{1/2} = \frac{a}{\sqrt{2}} \tag{50}$$

Thus Equation (5-18) becomes

$$\sigma_\tau = \frac{1}{a(E/N_o)^{1/2}} = \frac{1}{(a\,\pi\, s(o)^2 / N_o)^{1/2}} \tag{51}$$

Now $S(O)^2/N_o$ will be converted to a carrier-to-available-noise power density ratio and the parameter, a, will be expressed in terms of the antenna beam width (in the narrow dimension) θ_h, the angle ξ between the normal to the fan beam and the satellite's spin vector and ω_s. If $2\theta_h$ is the width of the beam from one half-power point to the other (in the narrow dimension of the fan beam), then

$$a = 1.18(\omega_s \sin \zeta)/\theta_h \tag{52}$$

Assume that the load impedence seen looking into the pre-amplifier is matched to the source or output impedance at the output of the cable from the antenna. Both of these impedances will be assumed real and equal to R_s. The input signal to the preamp will be of the order of where G is the gain between the input and the detection point. The peak value of $e(t) = G^{-1}S(O) \cos \omega_c t$ for t in the neighborhood of the peak, i. e., $|t| << a$. The signal power available to the load at this point in time (which will determine the peak transmitter power) is

$$P_{av} = \frac{G^{-2} S(O)^2}{4R_s} \tag{53}$$

The single-sided power spectral density of the noise voltage at this point is

$$G^{-2} N_o = 4k\, T_N R_s = 4N_{iav} R_s \tag{54}$$

where N_{iav} is the input stage available noise power (to load) per Hertz. Assuming that the signal-to-noise ratio at the input stage is equal to the signal-to-noise ratio at the detection point,

$$\frac{s(O)^2}{N_o} = \frac{R_s G^2 P_{av}}{4k\, T_N R_s G^2} = \frac{P_{av}}{k\, T_N} = \frac{P_{av}}{N_{iav}} \tag{55}$$

Substituting 51, 52, and 53 into 46 yields

$$\sigma_\phi = \frac{\omega_s}{\sqrt{2}} \sigma_\tau = 1/2 \left(\frac{2\, \omega_s \quad \theta_h}{(1.18) \quad \sqrt{\pi} \sin \quad \zeta}\right)^{1/2} \left(\frac{P_{av}}{N_{iav}}\right)^{1/2} \tag{56}$$

or

$$\frac{P_{av}}{N_{iav}} = \frac{1}{2\sigma_{\phi}^{2}} \left(\frac{\omega_s \ \theta_h}{(1.18)\sqrt{\pi} \ \sin \xi} \right) \tag{57}$$

Now, suitable design values are $\theta_h = 0.02$ radians, $\omega_s = 10$ radians/sec and $\xi = 45$ degrees. Letting $\sigma_{\phi} = 10^{-5}$ radians (which yields a 1 sigma navigation accuracy of approximately 1 n mi at a 10-degree elevation angle) gives

$$\frac{P_{av}}{N_{iav}} = 1.69 \times 10^{8} \ \frac{\text{watts}}{\text{watt/Hz}} \tag{58}$$

The satellite and user antenna gains for the fan beam concept are taken to be 29 db and 4 db, respectively. The link losses L_T are derived as follows:

User cable		0.8 db
Polarization and antenna losses		1.0 db
Atmospheric attenuation		2.0 db
L_T	=	3.8 db

For this concept, $T_{sky} = 80^{\circ}K$ which is made up of $50^{\circ}K$ due to atmospheric attenuation and $30^{\circ}K$ due to radiation from the ground into the main and side lobes of the user antenna. The carrier frequency for the fan beam concept is chosen as 8 GHz as the result of a complex trade involving antenna boom length, spin speed, θ_h, and satellite design. This trade is described in Reference 14. At this frequency, the contribution of galactic noise to T_{sky} is negligible. The receiver noise figure F is taken to be 5 db and the rf circuit losses are assumed to be 0.8 db. With these conditions, Equation 33 yields $T_N = 743^{\circ}K$. A power budget for the fan beam concept under these conditions is presented in Table 23.

Table 23 indicates that an unreasonably large amount of power is required to make the fan beam concept work. This is true both in terms of available spaceborne transmitting equipment, reasonable satellite design options that are likely to be available in the near future, and comparison with altitude alternate navigation satellite concepts. The transmitter power requirement is seen to vary inversely as the square of the standard deviation of the angular measurement accuracy. If the allowable measurement error were increased by a factor of ten (to the point where the 1 sigma position determination error would be 10-n mi at a 10-degree elevation angle of the line of sight and a 1.75-n mi error at a 90-degree elevation angle, then the peak transmitter power would be 8.9 kw, which is approaching a reasonable level.

Extensive studies in Reference 14 lead to the conclusion that there is little that one can gain with present technology in the accuracy-transmitter power trade. The most critical element in this trade is a method for decreasing θ_h, i.e., making the narrow dimension of the satellite fan beam appreciably less than 1 degree. The duty cycle of the fan beam concept at synchronous altitudes is $18^\circ/360^\circ = 0.05$. For the power budget in Table 23, this implies an average power of 44.5 kw. The fact that two fan beam channels are needed to determine the angular orientation of the line of sight does not help the satellite transmitter power problem. Also, in a practical receiver, the time of arrival of a pulse would probably be detected by threshold detection of the leading edge of the pulse to decrease the user equipment cost. Section III of Reference 38 shows that this will imply an increase in the transmitter power requirement by approximately 4.8 db to maintain the same level of accuracy as the optimum estimator for time of arrival.

The reason for the high transmitter power requirement in the fan beam concept can be explained in another manner. With $a = 1.18\,\omega_s \sin \zeta/\theta_h$, then the rise time for the Gaussian pulse is approximately $2a^{-1}$. With $\omega_s = 10$ radians/sec, $\theta_h = 0.02$ radians and $\zeta = 45$ degrees, $a = 420\ \text{sec}^{-1}$ and $2a^{-1} = 0.0048$ sec. With a spin rate of 10 radians per second, an angular error of 10^{-5} radians (which will yield a navigation error of the order of 1-n mi at a 10-degree elevation angle) implies a timing error of 10^{-6} seconds. Therefore, these design conditions on the fan beam navigation satellite concept imply a requirement to measure the time of arrival to an accuracy of one microsecond of a pulse whose rise time is of the order of 5 milliseconds. This requires a very high signal-to-noise or energy-to-noise spectral density ratio under idealized conditions. Under practical conditions, it requires stability in the antenna pattern, receiver threshold, and receiver gain characteristics to less than 1 percent of their calibrated values. These requirements are unrealistic and, therefore, the spinning fan beam navigation satellite concept is not feasible at synchronous altitudes.

Table 23. Power Budget for Fan Beam Concept (One Fan Channel)

Peak transmitted power (890 kw)	89.5 dbm
Path loss ($L_{PA} = L_T G_t G_u L_{SP}$)	-174.1 db
Space loss (L_{SP}) (8 GHz)	-203.3 db
Available received power = P_{av}	-84.6 dbm
Available noise power per Hz = N_{iav} (T_N = 743°K)	-169.9 dbm/Hz
P_{av}/N_{iav} (3.37 x 10^8 watts/watt/Hz	85.3 db Hz
(Equation 5-29 with 3 db margin)	
Margin (for 1-n mi 1 sigma navigation accuracy at a 10 degree elevation angle. Required peak power $\alpha 1/\sigma_\theta^2$).	3 db
Duty cycle = 0.05	
Average transmitted power	44.5 kw

Smoothing or averaging over many measurements will reduce the transmitter power requirements to some extent. For example, a spin rate of 10 radians per second implies a data rate of approximately three angular measurements per second. Smoothing over a three second interval or ten measurements would yield a reduction in the peak power requirements by a factor of ten. This smoothing interval is not large enough to reduce the required peak transmitter power to a reasonable level.

Longer smoothing intervals would create problems with high speed users unless complicated data processing techniques were used. It is doubtful that long smoothing times will reduce the errors with the efficiency associated with independent measurement errors.

The effects of correlations among different measurements due to such factors as biases and shifts in the antenna pattern characteristics and receiver thresholds would negate the improvement in accuracy and transmitter power requirements that could be obtained with smoothing. Therefore, it does not appear that smoothing will guarantee an attractive improvement in transmitter power requirements. The improvement that could be expected due to smoothing is difficult to predict without experimental data.

5.5 POSITION DETERMINATION ACCURACY

In this section, the factors affecting position determination accuracy capabilities on the different concepts are discussed. The measurement error sources associated with the interferometer, active ranging, and passive ranging concepts are summarized. The characteristics associated with the propagation of measurement errors and other effects such as satellite ephemeris errors into user navigation errors are discussed. The navigation accuracy capabilities of the ranging and interferometer concepts are summarized. Position determination accuracies for the various recommended navigation/traffic control satellite system constellations are presented in Volume II, Section 4.

5.5.1 Range Measurement Concepts

There are two general ways to use range measurements from satellites for navigation. One involves the use of range differences to determine the user's position in a manner that is analogous to hyperbolic navigation techniques such as Loran. The other uses range measurements (which may possess a common bias error due to the lack of synchronization between the user's clock and the satellite clocks) to determine position using the intersection of several spheres whose centers are located at the satellites. This latter approach can be considered an elliptical navigation technique in the sense that the locus of points which have a constant range sum to two fixed points (the focii of the ellipsoid which will be the satellite's location in this case) is an ellipsoid. A combination of these two techniques can be used to navigate. For example, a measurement of altitude can be considered as equivalent to a range measurement from the center of the earth and used in conjunction with range difference data to determine the user's position, or range data from some satellites and range difference data from other satellites can be used. With range measurements containing a large common bias, four satellite range measurements, three range measurements and user altitude, three independent range difference measurements (from four satellites), or two independent range difference measurements (from three satellites) plus user altitude will suffice to determine the user's position in cases with suitable relative locations between the user and the satellites. With a constellation of satellites and different data processing options involved in user position determination, correlation between different error sources can plan an important role in the accuracy of a ranging concept. A qualitative discussion of this phenomenon follows.

Let (x_u, y_u, z_u) represent the user position in a suitable Cartesian coordinate system, (x_i, y_i, z_i) represent the location of the i^{th} satellite and R_i represent the range between the i^{th} satellite and the user. Then, for the i^{th} satellite in the constellation,

$$R_i = \sqrt{(x_u - x_i)^2 + (y_u - y_i)^2 + (z_u - z_i)^2} \tag{59}$$

Let $\underline{\Delta X}_u$ represent the vector error (or deviation from the true value) in the determination of the user's position, $\underline{\Delta X_i}$ represents the tracking error associated with the i^{th} satellite, b the common bias due to lack of synchronization between the user's clock and the satellites' clock, and N_i the error in the range measurement between the i^{th} satellite and the user due to such effects as thermal nois· and refraction errors. N_i does not include the effects of satellite ephe..eris errors. A minimum variance estimation technique for position determination will be assumed here in order to illustrate the effects of correlations and relative geometry of the navigation process. Also, the effect of the user's velocity will be neglected in this discussion since it will introduce complications that are not pertinent to the effects of correlations in the static case. Of course, other techniques besides minimum variance estimation are feasible, and the effects of user velocity must be considered for high speed applications such as the SST. These considerations will be treated further in the section on user software. Under these conditions, the vector range observation error, $\underline{\Delta y}$, will be given by

$$\begin{aligned} \underline{\Delta y} &= [H]\,[\underline{\Delta X}_u] + \underline{N} + [B]\,b - \sum_{i=1}^{n} A_i\,\underline{\Delta X_i} \\ &= [HB]\begin{bmatrix} \underline{\Delta X}_u \\ \hline b \end{bmatrix} + \underline{N} - \sum_{i=1}^{n} A_i\,\underline{\Delta X_i} \end{aligned} \tag{60}$$

$$B = \begin{bmatrix} 1 \\ \cdot \\ \cdot \\ \cdot \\ 1 \end{bmatrix} \text{ - (an nxl matrix with each element unity)} \tag{61}$$

$$H = \begin{bmatrix} \frac{x_u - x_1}{R_1} & \frac{y_u - y_1}{R_1} & \frac{z_u - z_1}{R_1} \\ \frac{x_u - x_2}{R_2} & \frac{y_u - y_2}{R_2} & \frac{z_u - z_2}{R_2} \\ \vdots & \vdots & \vdots \\ \frac{x_u - x_n}{R_n} & \frac{y_u - y_n}{R_n} & \frac{z_u - z_n}{R_n} \end{bmatrix} = \begin{bmatrix} \ell_{1x} & \ell_{1y} & \ell_{1z} \\ \ell_{2x} & \ell_{2y} & \ell_{2z} \\ \vdots & \vdots & \vdots \\ \ell_{nx} & \ell_{ny} & \ell_{nz} \end{bmatrix} \tag{62}$$

$\ell_{ix}, \ell_{iy}, \ell_{iz}$ = the direction cosines between the line of sight to the i^{th} satellite and the x, y, z axes.

$A_i = D_i H$

D_i = an nxn matrix whose elements are all zero, except for the i^{th} diagonal element which is unity.

$\underline{N}$ = an nxl matrix whose i^{th} component is N_i

The state vector consists of the user position and the bias due to the lack of synchronization between the user and satellite clocks. In this discussion, it is assumed that the navigator estimates user position and bias b. Assuming that no a priori information about the state vector is available in the estimating process, the covariance of the estimated state vector is given by*

$$\text{cov} \begin{bmatrix} \underline{\Delta X}_u \\ b \end{bmatrix} = \left[(HB)^T \left(\Lambda_N + \sum_{i=1}^{n} \sum_{j=1}^{n} A_i \left(E \underline{\Delta X}_i \, \underline{\Delta X}_j^T \right) A_j^T \right)^{-1} (HB) \right]^{-1}$$

$$\Lambda N = E\left(\underline{N}\,\underline{N}^T\right) \tag{63}$$

E = mathematical expectation operator

Superscript T denotes the transpose of a matrix

---

*This assumes an optimal estimate using a weighting matrix which accounts for the satellite estimation errors. The user software will provide a simpler estimate with a diagonal weighting matrix, but results given in Volume II of Reference 1 show that the errors computed from Equation 63 will be very close to those achieved with the suboptimal estimate.

The covariance matrix of the state vector is an important indicator of navigation accuracy. Equation 63 shows that the following three factors determine this covariance matrix:

a) The H and A_i matrices which are determined by the orientation (direction cosines) of the lines of sight to the different satellites.

b) The covariance matrix of the measurement errors Λ_N - the measurements to different satellites will have some degree of correlation which will affect accuracy.

c) The terms of the term $E\, \underline{\Delta X_i}\, \underline{\Delta X_j}^T$ which represent the effect of satellite ephemeris errors—the cases where i = j involve the second moments of the errors for the i^{th} satellite while the cases where $i \neq j$ involve the effects of correlations between the ephemeris errors of different satellites.

If some combination of range difference measurements is used for navigation, then the observation errors can be written as

$$\begin{aligned} \underline{\Delta y}_1 &= F\, \underline{\Delta y} \\ &= [F]\,[HB] \begin{bmatrix} \underline{\Delta X}_u \\ \hline b \end{bmatrix} + [F]\,\underline{N} - \sum_{i=1}^{n} F A_i\, \underline{\Delta X}_i \end{aligned} \qquad (64)$$

The matrix F will typically be composed of zeroes, ones, and minus ones and forms some combination of range difference and range variables from the original range measurements. Under these conditions, Equation 63 becomes

$$\operatorname{cov} \begin{bmatrix} \underline{\Delta X}_u \\ \hline b \end{bmatrix} = \left[(FHB)^T \left(F\, \Lambda_N\, F^T + \sum_{i=1}^{n} \sum_{j=1}^{n} F A_i \left(E\, \underline{\Delta X}_i\, \underline{\Delta X}_j^T \right) A_i^T\, F^T \right)^{-1} (FHB) \right]^{-1} \qquad (65)$$

It is shown in Reference 1, Volume II, pages 75 and 77, Reference 39, by partitioning the covariance matrix, that under reasonably general conditions with range difference measurements the position determination accuracy $E\, \underline{\Delta X}_u\, \underline{\Delta X}_u^T$ is the same that one obtains with four biased range measurements. If F has an inverse (as it will in the case where n-1 range differences and one biased range measurement are used), then this fact can be demonstrated by straight forward matrix manipulation involving the factoring of F from the inner terms. If F does not have an inverse, this involves a more complex proof. If one or more of the range measurements does not have the common user clock bias associated with it (which will be the case when an altimeter measurement of altitude is used for navigation), then the nature of the HB and Λ_1 matrices in Equations 63 and 65 will change slightly (in addition to changes in the measurement error covariance). This will modify the navigation accuracy that one obtains. In addition, if the constellation possess extra satellites (for redundancy in case of failure), the extra observations that will be available can be used to improve accuracy to some extent. Finally, different implementations of the measurement process will result both in different standard deviations for the ranging errors and different correlations among the various sources that cause ranging errors. These questions are discussed briefly in the succeeding sections and in detail in References 22, 24, and 26.

5.5.1.1 Measurement Error Sources for Passive Ranging Concept

Navigation is performed in the passive ranging concept by using measurements of range from several different satellites. If the user's receiver has several different channels and the satellites can broadcast simultaneously without causing interference, then simultaneous range or range difference measurements can be obtained and used in navigation. However, if only one channel is available in the user's receiver, then range (or biased range) measurements are obtained sequentially in time. If range difference measurements are used in the position determination process, then this difference in times of validity of the two range measurements that form the range difference must be considered in the design of a system for high speed users. In a passive ranging system designed around the BINOR ranging code, one biased range measurement can be made about every 1.5 seconds. With CW or pseudo-random noise ranging codes, the measurement rate is of the order of 30 to 70 percent of the above rate depending on the radiated power from the satellite, the user receiver noise bandwidth, carrier acquisition time requirements, etc. The passive range code mechanization measurement error sources are summarized in Table 24. Corresponding range difference measurement errors are also listed there. Further information on the passive ranging error sources and their origins are given in Reference 26. The figures in Table 24 apply to a user who requires moderate accuracy. A reduction of the measurement errors in Table 24 to between 50 percent and 70 percent of the indicated values is feasible with the aid of more complex equipment, more frequenct and complex calibration procedures, and compensation in the user software.

5.5.1.2 Measurement Error Sources for Active Ranging Concept

The error sources associated with range measurements in an active ranging concept are quite similar in many respects to those associated with the passive ranging concepts. There are two important exceptions. First, the active ranging concept involves several transmissions over paths between the ground station and the satellite and the user. Therefore, the multiple transmissions will cause some error sources such as ionospheric refraction to produce different effects than they would in the passive ranging concept (where there is only one transmission of a ranging signal). Second, the ranging signal is retransmitted (transponded) by the satellite and the user. Any uncertainties in or uncalibrated variations of the delays in these transponders will result in range measurement errors. Current estimates indicate that transponder delay undertainties will constitute a dominant measurement error source for an L-band system (see Reference 22). An investigation of a VHF active ranging mechanization summarized in Reference 24 indicates that the ionospheric errors will be dominant at this carrier frequency.

The measurement errors for the pulse compression active ranging mechanization with an L-band carrier are summarized in Table 25. More detail is provided in Reference 22. While a detailed investigation of the measurement errors with a digital matched filter mechanization has not been performed, it is believed that they would not differ markedly from those in Table 25. The elevation sensitive errors assume that the elevation angle is a uniformly distributed random variable between 10 and 90 degrees.

5.5.1.3 Position Determination Accuracy with Passive Ranging

The discussion in Section 5.5.1 indicates that the conversion of range measurement and tracking errors into position determination

Table 24. Passive Range Measurement Errors (Moderate Accuracy User)

Source	Standard Deviation		Correlation Properties	Important Factors
	Range error ft(1σ)	Range Difference error ft (1σ)		
Tropospheric Refraction	3	1	Temporal and spatial correlation between measurements.	Varies inversely as sine of elevation angle. Magnitude and correlation depend on temperature and humidity profiles, etc.
Ionospheric	18	12	Temporal correlation strong over several measurement intervals. Spatial correlation high. Both depend on iospheric characteristics.	Varies inversely as carrier frequency squared and elevation angle. Depends on electrons in ray path. Latitude dependent. Assumes L-band carrier frequency.
Multipath	19	26	Some temporal correlation.	LOS orientation and reflected signal characteristics. Antenna gain pattern.
User Velocity	0	0	Negligible with suitable estimation technique and use of Doppler information.	
Satellite Oscillator	10	14	Temporal correlation.	Oscillator calibration procedures with tracking network and ground software.
Receiver Drift	12	17	Some temporal correlation.	A strong function of receiver design and calibration procedure.
Thermal Noise	14	20	No temporal correlation between measurements.	Receiver noise figure, noise seen by antenna, received signal power.
User Clock Quantization	12	16	No temporal correlation between measurements	User clock counter frequency and synchronization of clock to ranging signal.
RSS	36	44		

(1) Range difference measurement error.

(2) Mean ± standard deviation. Some compensation for mean possible.

(3) The effect of these error sources can be reduced to between 50% and 70% of the above values in a user that requires the highest accuracy. This is accomplished by software compensation techniques, user equipment calibration procedures, and high quality equipment.

(4) Elevation angle dependent errors are averaged over elevation angeles between 10° and 90° by assuming a uniform distribution.

Table 25. Range Measurement Error Sources for Active Ranging Concept with Pulse Compression Mechanization (Moderate Accuracy User)

Error Source	Standard Deviation	Correlation Properties	Important Factors
	Range error, ft		
Tropospheric[2] refraction	3	Temporal and spatial correlation among measurements	Dependent on atmospheric characteristics such as temperature and humidity profiles. Varies as co-secant of elevation angle.
Ionospheric[2] refraction	18	Strong temporal and spatial correlations depends on electron distribution in ionosphere.	Latitude dependent. Varies inversely as elevation angle and inversely as square of carrier frequency.
Thermal noise	14	No temporal or spatial correlation between measurements.	Received signal power, receiver noise figure, noise seen by antenna.
Doppler shift	7	Temporal correlation.	Determined by variarions in matched filter characteristics with frequency. Caused by variation in delay in matched filter with frequency. Can be compensated.
AGC shifts	7	Temporal correlation.	Depends on transponder design.
Threshold fluctuations	3	Temporal correlation.	Depends on transponder design.
Repeater delay uncertainties	65	Temporal correlation.	Strongly dependent on user equipment calibration and ground station software compensation.
RSS	69		

[1] These values pertain to a high accuracy, high speed user such as the SST.

[2] These elevation angle dependent error sources are affected by orientation of the satellite-ground station line of sight as well as satellite-user line of sight. Numbers here represent average over a range of elevation angles between 10 and 90 degrees with uniform distribution over this range.

errors is a complex process (which is dependent on the satellite constellation). For the North Atlantic Ocean Area Air Traffic Control application, a synchronous equatorial satellite constellation has the attraction of making all of the satellites visible to the user most of the time. With a constellation of four synchronous equatorial satellites with sub-satellite points spaced evenly across the Atlantic Ocean, the results in References 20, 27, and 28* indicate that for the navigation error (which is defined below) will be between 0.1 n mi and 0.5 n mi in the North Atlantic. C-95 is defined as the radius of the circle inside which 95 percent of the navigation errors associated with an ensemble of trails will be located. As the user gets closer to the equator, the accuracy will degrade to a C-95 approaching 1-n mi at a lattitude of 10 degrees. There are several reasons why the accuracy varies by a factor of five. First, the tracking process will cause both the magnitude and correlations of the satellite errors to be time-varying. In addition, the tracking accuracy will vary with the number and location of the stations in the ground tracking network. Appendix H of Volume II of Reference 1 indicate this trend. Thus, the satellite ephemeris errors can in many instances make a greater contribution to navigation errors than the range measurement errors shown in Table 24. Finally, the use of altitude information and other sources of measurements with the element of redundance will affect the navigation accuracy.

If some of the satellites are placed in inclined orbits such as the 18.5 degree orbits used in Reference 1, then the accuracy will improve to the point where values of C-95 of the order of 0.05 n mi are feasible in the North Atlantic with the measurement errors shown in Table 24. With satellites in inclined orbits, the accuracy in the equatorial region improves to a C-95 level of the order of 0.05 n mi to 0.1 n mi. Thus, one of the major effects of using a constellation with inclined orbits is to make a marked improvement in accuracy near the equator. However, if an inclined orbit is used for some of the satellites in the constellation, then not all satellites will be visible to any specified user at one time. Consequently, more satellites will be needed to ensure that enough satellites are available for position determination at all required points on the

*Navigation accuracies were computed using the MSAT and NAVSAP programs described in Appendices B and J of Reference 1, Volume II.

globe at all times. A minimum of three satellites is needed to cover the North Atlantic area with a synchronous equatorial constellation while at least four will be required with a constellation with inclined orbits. Reference 40 discusses the accuracy-coverage trandeoff for different worldwide constellations in great detail.

In Reference 38, it is shown that for nonredundant range measurements the sensitivity (in a two dimensional situation) of the user position determination error to a single range measurement error varies between 1. 0 and 2. 25 in the North Atlantic for a synchronous satellite, while the corresponding sensitivity to altitude measurement errors varies between 2 and 0. 25. While these numbers are based on a grossly simplified analysis and do not account for correlations between measurements and satellite ephemeris effects, they do indicate crudely, an order of magnitude relationship between measurement errors and navigation errors. This approach can also be extended to three dimensions with suboptimal measurement data processing. This extension and Reference 38 both indicate that passive ranging navigation accuracy improves as the satellites become more separated in terms of angles between their lines of sight.

5. 5. 1. 4 Position Determination Accuracy with Active Ranging

A comparison of the measurement errors for the active ranging concept shown in Table 25 with those for the passive ranging concept shown in Table 25 indicates that the predominant error for the active ranging concept is due to repeater delay uncertainties and most of the other error sources are similar in magnitude. The effect of repeater delay uncertainties increases the error in active range measurement by a factor of about two compared with the passive range measurement concept. This increase is not a factor to which one can attach a great deal of precision since repeater delay uncertainties will depend on such system design details as transponder calibration procedures which are uncertain at this stage of the system definition. It might be possible to reduce repeater delay uncertainties to a negligible level with elaborate calibration procedures. For example, repeater delay might be estimated in connection with the navigation computations at the ground station. On the other hand, a user who does not desire good navigation accuracy could utilize cheaper equipment and less involved calibration procedures.

The geometric and correlation considerations associated with range measurement concepts that were discussed in Paragraph 5.5-1 apply to active ranging. Some of these effects are discussed in References 22 and 24. Thus, the active ranging concept will have the same order of magnitude of accuracy as the passive ranging concept. At L-band, this should be between 0.05 n mi and 0.5 n mi in the North Atlantic Ocean area depending on such items as satellite ephemeris errors, user-satellite locations, and correlations.

5.5.2 Passive Interferometer Concept Accuracy

5.5.2.1 Mechanization of the Passive Interferometer Concept

The passive interferometer concept uses signals from a transmitting interferometer with two orthogonal baselines located in the satellite to determine the orientation of the line of sight to the satellite. A user altitude measurement plus the line-of-sight orientation permits the user to determine his position. Since only one satellite is involved in the position determination process, the questions of correlations among the measurements are not as complex as they are for the active and passive ranging concepts where several satellites are used to determine position. There is one effect due to the orientation of the user's line of sight to the satellite which is quite important. This is the effect of elevation angle on the sensitivity of navigation error to angle measurement error which is given in Equation 42 and is reproduced below.

$$\delta P_1 = R\delta\theta \csc E = \frac{R\delta\phi_1}{2\pi n} \frac{\csc E}{\sin \theta} \qquad (66)$$

This equation is actually valid for an angular error about one axis which will be called the roll axis and will correspond to the error in the north-south direction for the case where the user is in the North Atlantic and the satellite in a synchronous equatorial orbit. The corresponding east-west error will be given by

$$\delta P_2 = \ell\delta\theta_2 + R\delta\theta_3 \qquad (67)$$

Where $\delta\theta_2$ is the angular measurement error about the yaw axis and $\delta\theta_3$, the angular measurement error about the pitch axis. The large values of R (22, 700 n mi) and ℓ (3400 n mi or less) require angular measurement accuracies of the order of 8 μrad about the roll axis to achieve a navigation accuracy of 1 n mi with a 10 degree elevation angle. ℓ is the perpendicular distance from the user to the satellite local vertical.

The above requirements for angular measurement accuracy imply the same types of tolerance on the attitude control system errors in the satellite (or more precisely, on the orientation error of the two interferometer baselines). Control of the baseline orientation with the attitude control system to this tolerance is not feasible with present technology according to Reference 32. If any interferometer concept is to prove feasible at synchronous altitudes, a solution to this problem must be found. Even if the control system performance could meet these tolerances with a rigid satellite, such disturbances as transients in the attitude control system due to boom bending excited by thermal inputs resulting from eclipses of the satellite will make it impossible to meet these tolerances by attitude control system design. These problems are discussed in more detail in Reference 32. The most practical solution to this problem is a compensation scheme which uses a network of several ground stations whose location is known to measure the attitude of the baselines, generate phase and frequency compensation signals, and transmit them to the satellite where they are used to alter the outputs of the transmitting interferometer. The compensation process attempts to make the signals from the baseline look like they were transmitted from an interferometer with the proper orientation. This technique of compensation is described in detail in Paragraph 5. 5. 2. 3 and in References 34 and 35. Its success is crucial to the feasibility of an interferometer concept.

Another important question relating to the feasibility of an interferometer concept is the feasibility of measuring the phase difference between two signals to high levels of accuracy. Under laboratory conditions, it has been demonstrated that the phase difference can be measured to an accuracy of better than a tenth of a degree. Under field operating conditions, problems have been encountered in some systems with measuring electrical phase to an accuracy of the order of one degree. Such problems are apparently due to bias and calibration instabilities. The effect of this type of error on navigation accuracy is shown in Equation 38 and influences the design of the navigation link discussed in Section 4. 5.

The strongest influence is in the trade between boom length and accuracy.

5.5.2.2 Passive Interferometer Measurement Errors and Navigation Accuracy

The measurement and navigation error sources associated with the passive interferometer concept are shown in Table 26. Note that the capability of the compensation scheme is an important factor in the interferometer's accuracy. The unknown nature of its capabilities make the interferometer navigation error an open question at this time. This question is difficult to resolve without building a demonstration system and testing it. Further details on the interferometer error budget are presented in References 34, 35, and 41.

5.5.2.3 Compensation of Interferometer Errors

It is generally conceded that an interferometer satellite cannot be controlled with an angular accuracy of 10 to 50 μrads, which is required for a 1 n mi system. It is therefore necessary to provide an error correcting or compensating scheme to reduce orientation and antenna distortion errors to an acceptable level. The remarks in this section apply to both passive and active interferometers.

The most feasible correction scheme, with either a transmitting or receiving interferometer, is to correct the phase and frequency of the interferometer based on signals from dedicated ground stations. In this approach, the interferometer receives signals from certain ground stations with known locations and by suitably adjusting the phase of frequency of the signals forces the measured angle to the ground station to coincide with the true angle. Unfortunately, only two attitude angular errors can be compensated this way. The third can be measured and corrections made in a different manner. This is shown later.

No attempt will be made here to analyze the compensation system because a baseline design does not exist at this time. The following discussion is limited to estimating the requirements imposed on the compensation system by a 10 to 50 μrad overall angular accuracy requirement.

Table 26. Measurement and Navigation Errors for Passive Interferometer Concept (X-Band)

Source	Angle Measurement Error	Navigation Error ($E = 10^{o}$)	
Ionospheric refraction	0.07 μrad	.009 nmi	Varies inversely with carrier frequency squared and as cot E csc E. Depends on properties of ionosphere. Compensation possible to +100 to 50 percent of nominal.
Tropospheric refraction	0.18 μrad	.023 nmi	Varies as cot E csc E. Depends on properties of troposphere. Compensation possible.
Thermal noise and phase	0.028 rad (electrical phase) or 22 μrad (LOS angle)	2.8 nmi	Assumes baseline of 200 wavelengths and equal errors due to noise and biases.
Multipath	35 μrad	4.4 nmi	Features conservative assumption on reflected signal magnitude. Applies to SST user at 80,000 ft.
Dynamic tracking lag	4 μrad	0.5 nmi	Assumes second order tracking filter with noise bandwidth of 0.25 Hz.
Attitude control	17.5 μrad	2.2 nmi	Involves compensation for yaw, pitch, and roll error, boom shortening, and residual error. Attitude control to $\pm 0.1^{o}$ (1 sigma); compensation to 1 percent. An uncertain factor. Feasibility of compensation yet to be demonstrated.
		RSS = 5.6 nmi	

Attitude Error Compensation. Consider the sketch in Figure 72 that defines the coordinates associated with an interferometer satellite and two calibration stations that transmit normal signals which are the same or similar to those of a user for a receiving interferometer. The interferometer measures an angle between the line of sight to the station and a line that passes through the antennas (see Figure 73). Thus, interferometer X measures angles XA and XB between its sensitive axis and the LOS to station A and B, respectively. For simplicity, station B is shown in the Y-B plane and A in the X-A plane, but this is not a requirement. If only small rotations about the nominal interferometer attitude are considered, equations relating attitude error to the measured angle of the line of sight from the ground station can be written.

The attitude errors are found to be:

$$\Delta\phi = \frac{C(YB)_M - C(YB)_D}{S(YB)_D} = -\Delta(YB) \qquad C = \text{cosine}$$

$$S = \text{sine}$$

$$\Delta\theta = \frac{C(XA)_M - C(XA)_D}{S(XA)_D} = \Delta(XA)$$

$$\Delta\psi_X = \frac{C(XB)_M + \delta\theta\, S(YB)_D}{C(YB)_D} = \text{yaw error of the X antenna}$$

$$\Delta\psi_Y = \frac{\Delta\phi S(XA)_D - C(YA)_M}{C(XA)_D} = \text{yaw error of the Y antenna}$$

These equations may be used to generate signals to drive the attitude control system.

It is not possible to compensate, by phase adjustment, for all the attitude errors, because the interferometer measures the angle between its sensitive axis and the LOS. Inspection will show that it is not possible to correct a yaw error without introducing a pitch or roll error and vice versa. It is a case of trying to correct three things with two adjustments.

A suggested procedure is to correct for pitch and roll by phase adjustment and correct for yaw in some other manner. The yaw error

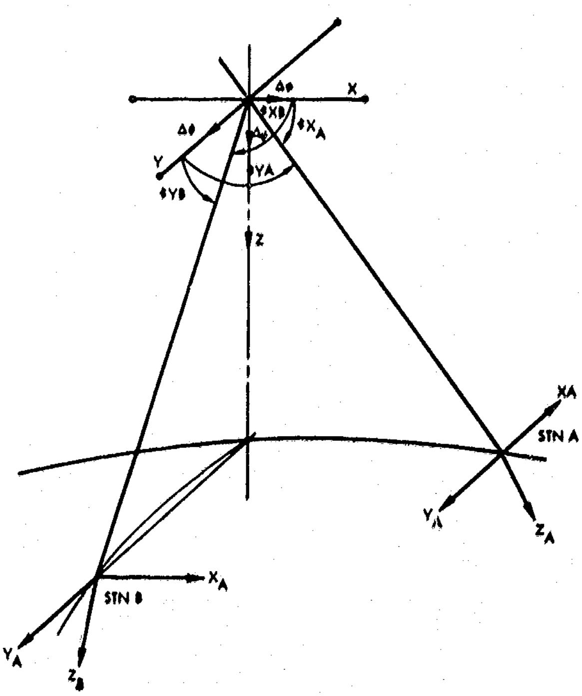


Figure 72. Interferometer and Ground Station Coordinates

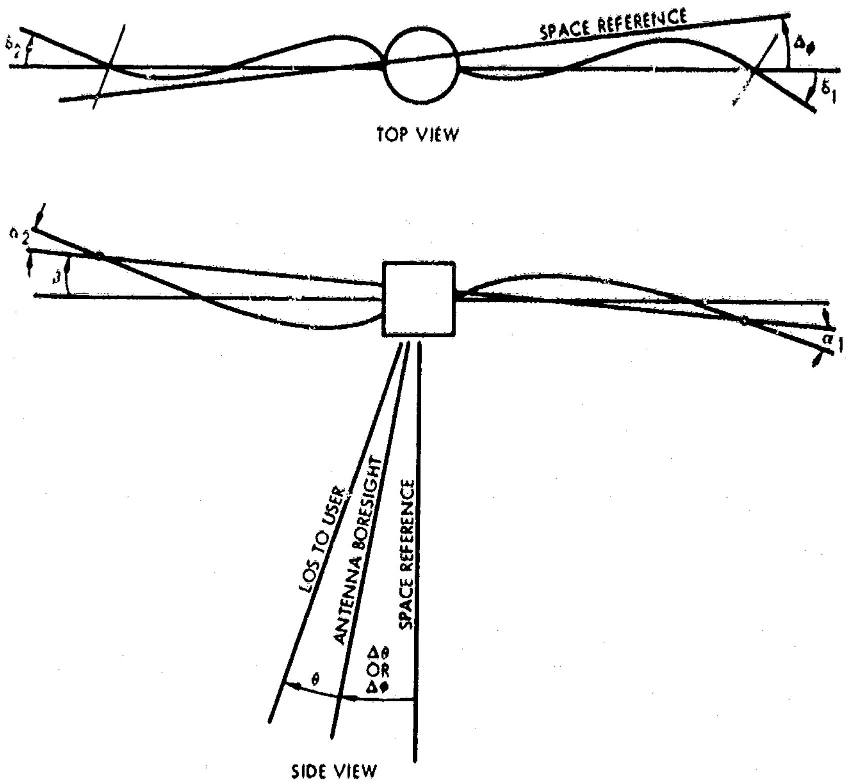


Figure 73. Definition of Satellite Angular Reference

is slowly varying so $\Delta\psi$ can be written in terms of constants and error angles as

$$\Delta\psi_X = \frac{C(XB)_D - S(XB)_D\,\Delta(XB) + S(YB)_D\,\Delta(XA)}{C(YB)_D}$$

$$\Delta\psi_X = K_1 + K_2\,\Delta(XB) + K_3\,\Delta(XA)$$

and

$$\Delta\psi_Y = \frac{-C(YA)_D - S(XA)_D\,\Delta(YB) + S(YA)_D\,\Delta(YA)}{C(XA)_D}$$

$$\Delta\psi_Y = K_4 + K_4\,\Delta(YB) + K_5\,\Delta YA$$

$\Delta\psi_X$ and $\Delta\psi_Y$ can be transmitted to the user or the ground station for inclusion in the position determination equations.

The effect of antenna boom tip slope differences (in fact all phase variations) will be interpreted by the calibration system as attitude errors. The system will compensate in pitch and roll for these imaginary errors and introduce an imaginary yaw error, $\Delta\psi_X$ and $\Delta\psi_Y$. When $\Delta\psi_X$ and $\Delta\psi_Y$ are accounted for in the navigation process, the boom tip, and other phase errors are eliminated.

Unfortunately, it is only possible to correct exactly for the pitch and roll errors at one point for each of the two antennas. Reference 21 shows that a residual error will exist as the user moves away from the reference station. This error may be expressed as:

$$\Delta_\gamma = (C\theta_U - C\theta_C)\, S\Delta\theta + (1 - C\Delta\theta)(S\theta_C - S\theta_U)$$

θ_U - angle between boresight and user

θ_C - angle between boresight and calibration station

$\Delta\theta$ - satellite angular error WRT local vertical

Δ_γ - residual error after phase compensation

If $\Delta\theta$ and $\Delta\phi$ are transmitted to the user or ground station along with $\Delta\psi$, the residual error could be compensated and reduced to a negligible value.

Reference 21 suggests that both frequency and phase be used to correct pitch and roll at two points. It is suggested that for a North Atlantic system, that phase be used to correct exactly at one point and frequency be used as suggested in the next section. If the calibration station is centered in the area of interest, the maximum difference between θ_U and θ_C is 4 degrees, and $\Delta\gamma$ will be 138 μr at $\Delta\theta = 1^\circ$. This is certainly a worst case, and reducible by compensation.

Boom Shortening Compensation. Shortening of the antenna booms due to bending can be accounted for by monitoring two calibration signals per antenna pair and either changing the transmitting frequency for a transmitting interferometer or the IF frequency for a receiving interferometer. The measurement and compensation can be done in the satellite with no transportation lag. Figure 74 illustrates the geometry of such

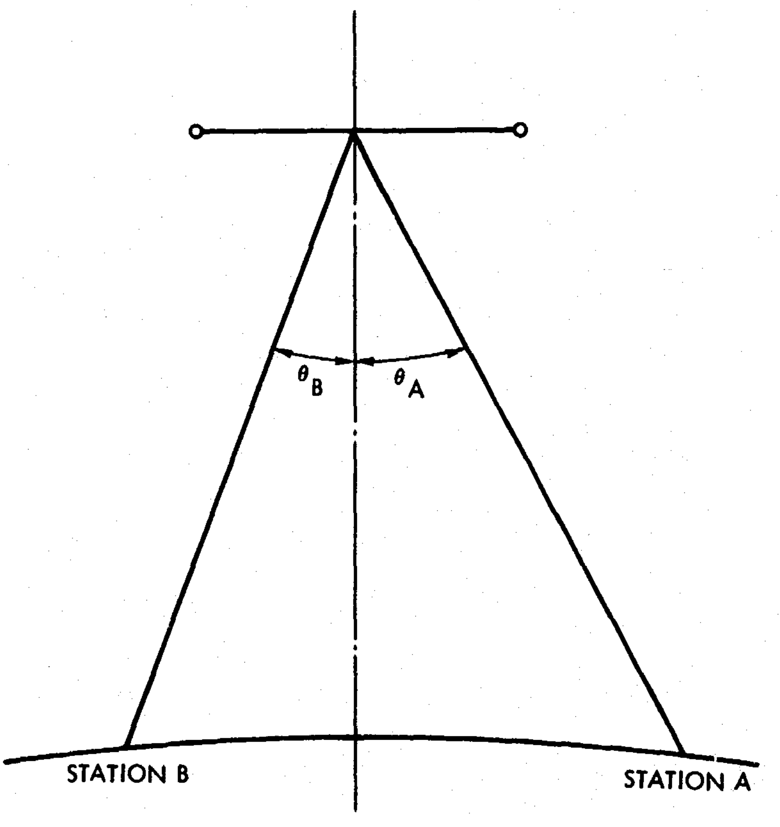


Figure 74. Compensation for Boom Shortening

a compensation technique. Two stations are required to eliminate attitude variations. For a given satellite altitude, the angles θ_A and θ_B are constant, and regardless of antenna attitude uncertainties, the sum of the two angles as measured by the interferometer should remain constant. The angles which are measured are related to the antenna geometry and electrical phase by the interferometer formula.

$$\sin \theta_A = \frac{\phi_A \lambda}{2\pi D}, \quad \sin \theta_B = \frac{\phi_B \lambda}{2\pi D}$$

$$\theta_A \text{ and } \theta_B < 8^\circ$$

therefore,

$$\frac{\phi_A \lambda}{2\pi D} + \frac{\phi_B \lambda}{2\pi D} \approx K \quad f\lambda = C, \quad K = \text{a constant}$$

$$D \approx \frac{(\phi_A + \phi_B)\lambda}{2\pi K}$$

λ can be adjusted to keep the effective baseline length of the antenna constant. Note that this technique also automatically compensates for satellite altitude variations.

An error will result in the above since sin θ_A is approximated by θ_A. This error is negligibly small. It can be shown that it would cause an error of less than 0.1 μrad in the L-band interferometer with a 1-degree attitude control system and a D/λ of 100.

5.5.2.4 Compensation System Requirements

In the preceding sections, it was shown that the compensation system was essentially that of adjusting the phase of two incoming signals such that they matched a reference phase for the case of attitude and phase errors. The compensation system for shortening required that frequency be adjusted so that the sum of the phase difference from two calibration stations remain constant. Two simple block diagrams depicting the problem are shown in Figure 75.

The system input to error transfer function is, in both cases:

$$\frac{\Delta\theta}{\theta_M} = \frac{S(S + 1/\tau)}{S^2 + S/\tau + k/\tau}$$

Assume the disturbance (in θ_M) is sinusoidal and that the input frequency is a rad/sec with a magnitude of M. Define:

$$S = j\omega$$

$$R = \frac{a}{\omega_o} = a\sqrt{\tau/k}$$

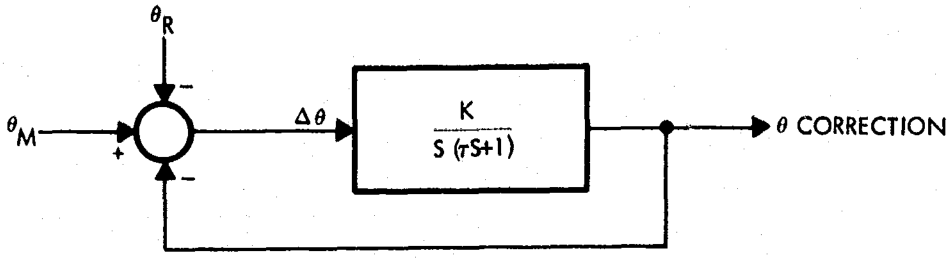
$$1/\tau = 2\zeta\,\omega_o = 2\zeta\sqrt{k/\tau}$$

Making the above substitutions and solving for the steady state error:

$$|\Delta\theta| = \frac{MR\sqrt{R^2 + 4\zeta^2}}{\sqrt{(R^2 - 1)^2 + 4R^2\zeta^2}} \sin at$$

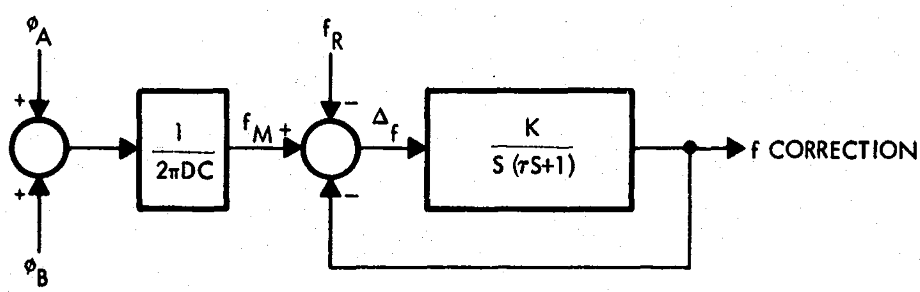
when R << 1

$$|\Delta\theta| = 2RM\zeta \sin at = 2\zeta M a \sqrt{\tau/k} \sin at$$



θ_M - MEASURED ANGLE
θ_R - REFERENCE ANGLE

A) ATTITUDE COMPENSATION



ϕ_A, ϕ_B - MEASURED PHASE DIFFERENCES

f_R - REFERENCE FREQUENCY

B) SHORTENING COMPENSATION

Figure 75. Attitude Compensation and Shortening Compensation

For a step input of magnitude M, the instantaneous $\Delta\theta$ equals the input, and it decays with an envelope of $e^{-1/2\tau}$.

Reference 33 shows that typical pipe booms (OGO satellite) have natural frequency and amplitude for the first asymmetric bending mode as shown in Table 27 for 1600 and 8000 MC booms which are 100 wavelengths long.

Table 27. Boom Natural Frequency and Amplitude

Length	33 ft (1600 MC)	6.6 ft (8000 MC)
Frequency	0.135 CPS	1.43 CPS
Amplitude	1.31 MR	0.004 MR

If it is assumed that this is the only vibration mode (a poor assumption), then the requirements on the compensation system can readily be seen. Let

$$|\Delta\theta| = 10 \ \mu\text{rad}$$

$$2\pi a = 0.135 \text{ CPS and } 1.43 \text{ CPS}$$

$$M = 1,310 \ \mu\text{rad and } 4 \ \mu\text{rad}$$

$$\xi = 0.7$$

Then for 1600 MC, $k/\tau = \omega_o = 25.8$ CPS and $k = 111$, at 8000 MC the error due to bending is within the allowable value of 10 μ rad.

To numerically evaluate the probable error of a system, two inputs are required: first, an estimate of the vibration frequencies and amplitudes and the attitude control amplitude and frequency, and second, an estimate of the response characteristics of the phase and frequency devices which are used to compensate for altitude and shortening errors.

The above simple analysis shows that a 26 CPS compensation system can handle the first asymmetric mode for bending and shortening. If the amplitude-frequency product of higher modes is less than the first asymmetric mode up to a maximum mode frequency of 8 to 10 CPS, then a 26 CPS system could handle a 66-ft L-band system.

5.5.3 Active Range and Angle Measurement Concept

The active range and angle measurement concept uses an active range measurement and an interferometric angle measurement made in the satellite to determine the user's position. The use of the range measurement in place of user altitude in the passive interferometer concept reduces the sensitivity of position determination errors δP_1 (see Equation 38 to angle measurement errors by a factor that can be as large as 15 for a user in the North Atlantic and as low as 1 for a user in the equator where the elevation angle will be 90 degrees. This geometric effect is discussed in detail in Reference 38. As a result, the tolerances on the orientation of the interferometer baselines are reduced proportionately. However, a compensation scheme similar to that discussed for the passive interferometer in Paragraph 5. 5. 2. 3 also will be required here. This error source and multipath could be predominant error sources and both constitute major unknowns at this time. However, the sensitivity to angle measurement errors of δP_1 is reduced by a factor between 1 and 15 as was noted above. The sensitivity of δP_2 (see Equation 40 to angle measurement errors is the same as was the case in the passive interferometer. The sensitivity of navigation errors due to range measurement errors varies between 0. 4 and 1. With range measurement errors of the order of 100 feet, the position determination errors due to this source will be negligible compared with the angle measurement errors. Thus, to a large extent, the same problems that affect the accuracy and feasibility of the active range and angle measuring concept. The difference is that the compensation requirements will not be as stringent (by a factor of the order of 10 to 15 at low elevation angles) for the active range and angle measurement concept.

5. 6 USER EQUIPMENT CHARACTERISTICS

This section summarizes the characteristics of the user equipment for the passive and active ranging concepts and the passive interferometer concept. The active range and interferometer concept has user equipment that is very similar to that of the active ranging concept. In fact, the major difference for one mechanization of the active range and interferometer concept would be the difference in signals transmitted from the user upon receipt of a ranging signal from the satellite. Other mechanizations of this concept, such as the digital matched filter, would also involve transponding the ranging signal and a CW signal used for interferometer measurements in a satellite. Consequently, no extensive discussion of the user equipment for the active range and angle measurement concept will be given here.

The primary emphasis in this section is cost comparison of the user equipment associated with the concepts considered.

5.6.1 Antenna Subsystem

The user antenna for all the concepts has been chosen as a low gain antenna with hemispherical coverage. The reasons for the choice of such an antenna are low antenna and overall system costs, operational simplicity and reliability in that steering the antenna beam will not be required, and the possibility of using different antenna configurations on users that have different operational requirements. For example, an SST will require an antenna that is flush mounted or nearly flush mounted with the aircraft skin, while the low speed aircraft or ship will require a simple sturdy antenna that can protrude a reasonable distance from the surface. Three antennas which look attractive for these different applications are the conical log spiral, the curved dipole turnstile, and a series of flush mounted slotted dipoles which are mounted in cavities and switched electrically.

The conical log spiral antenna is described in Reference 1 and is very suitable for use in applications where aerodynamic drag or protrusion from a surface is not a problem. The physical shape is similar to that of an ice cream cone. It is 7 inches high and about 5-1/2 inches in diameter. An estimated cost for this antenna is $220.

5.6.2 Software for Passive Systems

Several approaches are possible for the user software for determining position from measurements in passive systems. The implementation of position determination computations with a passive user will depend on the characteristics of the measurements for each concept. These characteristics are summarized in Table 28. However, in general, most of the passive concepts have three different approaches to position determination. The first involves an optimal Kalman filtering* or recursive minimum variance estimation procedure which accounts for all the correlations among the measurements in both a temporal and

---

*The Kalman filtering approach is most suitable for a sophisticated, high speed user such as an SST which has other sources of data. A less sophisticated user could interpolate the relative range measurements in the preprocessor to obtain a set valid at a common point in time and determine position with a simple algorithm in an inexpensive computer (see Volume II of Reference 1).

Table 28. Signal and Measured Data Characteristics

	Carrier Frequency and Pulse Rate	Measurement Time	Measurement Signal Bandwidth	Measurement Signal Modulation
Passive ranging	L-band	2 sec for R 6-8 sec for fix	1650 Hz acq. 60 Hz track	BINOR rapid acquisition CW code.
Pulse compression active ranging	100 pps L band	10^{-2} sec	2.2 MHz for FM pulse	FM pulse compression for pulse.
Digital matched filter active ranging	L-band	10^{-2} sec	2.2 MHz	Split phase modulation.
Active range and interferometer	100 pps L band-ranging C or S band-interferometer	10^{-2} sec	219 KHz for ranging	FM pulse compression for range. CW for interferometer.
Passive interferometer—depends on reference osc. frequency	X or C-band	1 sec (with averaging over 10-100 phase measurements)	1/2 Hz	CW
Fan beam[1]	3 pps X-band	0.3 sec	600 Hz	CW omitted, pulse received

(1) Also needs reference pulse which can have higher bandwidth.

spatial manner. The second approach represents the use of suboptimal filtering techniques whose characteristics will depend on the measurement scheme associated with a particular concept and the desire to attain the accuracy inherent in a given concept by accounting for all the correlations among the measurements. One example of the suboptimal filtering technique that has been considered for passive ranging involves the processing of range difference measurements as though they were uncorrelated when in fact they are not uncorrelated. Similarly, one can use a representation of the user's position (latitude and longitude) in terms of a polynomial in the measured variables. The polynomial represents an expansion about a reference point and would not require a complex data processing system for position determination. It can be used for all the passive concepts.

A schematic diagram which represents the processes involved in the computation of user position in passive systems is shown in Figure 76. The main differences* associated with the processes in each block will involve such items as different coordinates that one might use to represent the user state vector and the satellite ephemeris measurement matrices (which represent the sensitivity of the observation variables at the user to changes in the user's position), different computational rates associated with different measurement rates, and different requirements for ephemeris information such as satellite oscillator calibration data in a passive ranging concept and satellite attitude compensation at an interferometer concept. The differences between the concepts are those differences in communication requirements for such items as ephemeris data and the relatively small differences between concepts involving computing such items as measurement matrices. In the present status of the system definitions, these differences will not affect a choice among the different navigation concepts for a high accuracy user who will have a reasonably large general purpose digital computer available to him.

One difference that is pertinent to mention is that with a passive ranging system it will be easier to extract Doppler information from the range measurements and obtain user velocity then it will be to perform this operation with a passive interferometer system.

---

*Differences between the various concepts.

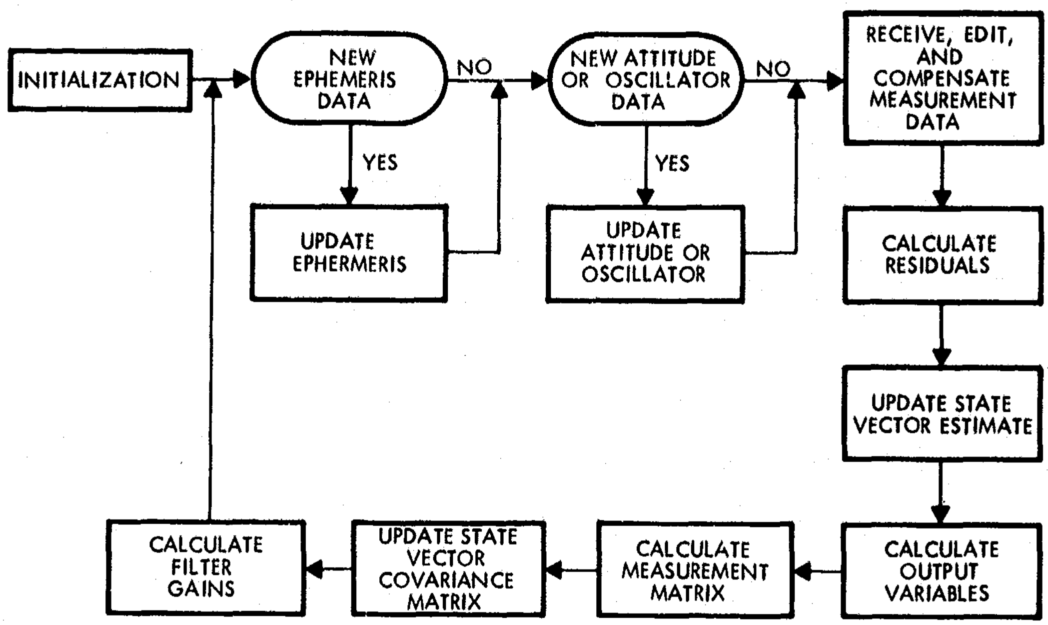


Figure 76. User Software and Computing Techniques for Passive Systems

5.6.3 Passive Ranging Concept

The user equipment for a BINOR ranging code mechanization of the passive ranging concept features an antenna, a receiver, a preprocessor, and some form of computer and display unit. The function of the receiver is to acquire and track the carrier with a phase lock loop. Once the carrier is acquired, the coded ranging signals are acquired through a resolution process which resolves the range ambiguity. The relative range (the range plus the user oscillator bias) is then determined. The mechanization of the BINOR system which is considered in References 1 and 26 involves making one measurement of range at a time. The measurement can be used to update the current estimate of the user state vector, or it can be combined with several other range measurements to make a separate determination of position (and perhaps velocity). It is then used to update the state vector. An alternate mechanization of the concept (which would be considerably more expensive in terms of receiver design) would be to mechanize the system capability to make several range measurements at once using parallel channels in the receiver. This would increase the data rate by a factor of three or four but complicate the user equipment design. A schematic diagram of the user equipment for the passive ranging concept is shown in Figure 77. The power budget for this concept is given in Section 5.4.1.

5.6.4 Active Ranging Concept

The user equipment for an active ranging concept consists of a receiver with an appropriate number of IF stages for amplification, a device consisting of logic circuitry which turns on the transmitter in the event that the ranging signal is meant for the particular user and a transmitter which sends the ranging signal back to the satellite. A diplexer or other isolation device is needed to prevent a strong signal from the transmitter from damaging the receiver front end.

5.6.4.1 Pulse Compression Active Ranging Concept

The design of a system for the pulse compression active ranging concept is presented in Reference 5. With this design, the addressing pulses are transmitted first in the ranging message. The addressing pulses are detected using a compressive delay line which is matched to the chirped signal. If the ranging pulses are intended for the particular user, the transmitter is then turned on. In the meantime, a nondispersive delay line (whose delay is constant over the signal frequency spectrum) receives the ranging pulses and sends them to the transmitter where they are translated in frequency, passed the several stages of amplification, and retransmitted. A schematic diagram of this concept is shown in Figure 78. A processing gain of 100 is used in the detection of the user addressing pulses. Time side lobes and component stabilities are not the problem with detection of the user address pulses that they present with the detection of the ranging pulses.

5.6.4.2 User Equipment for the Active Ranging Concept with the Digital Matched Filter

The user equipment for the digital matched filter consists of a receiver which estimates the carrier frequency with a phase locked loop and a discriminator and then retransmits the ranging signal, using this estimated carrier, back to the satellite. The schematic block diagram

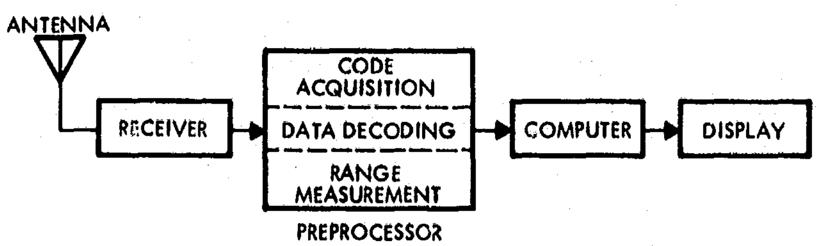


Figure 77. User Equipment for Passive Ranging Concept

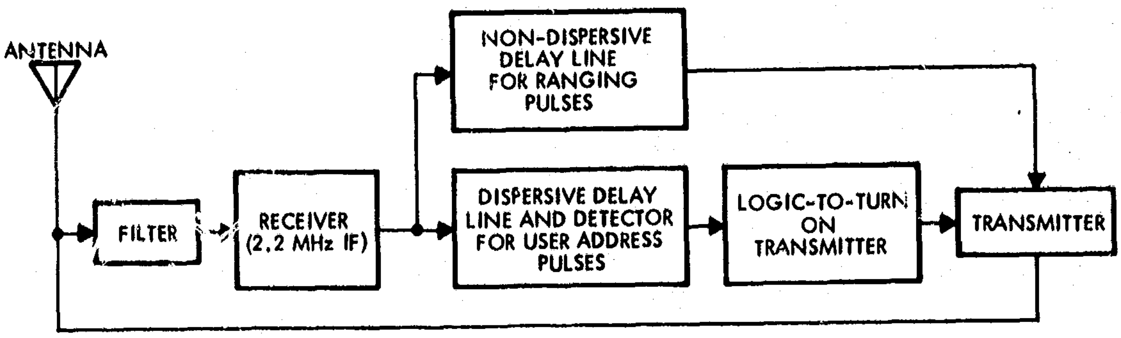


Figure 78. User Equipment for Pulse Compression Active Ranging Concept

of this transponder is shown in Figure 79. The user address information is contained in the phase modulated signal and decoded from the output of the phase locked loop after the carrier is acquired.

5.6.5 User Equipment for Passive Interferometer

The user equipment for the passive interferometer consists of an antenna, a receiver with a common IF phase measurement design to minimize differential phase shifts between the two received signals transmitted from the satellite, a preprocessor which converts this phase information into angle, and some form of computer display unit. A schematic block diagram of the user equipment for this concept is shown in Figure 80. A detailed design study of the user equipment for this concept was not undertaken since serious questions of feasibility (attitude control and boom bending) required solution in the work associated with the interferometer.

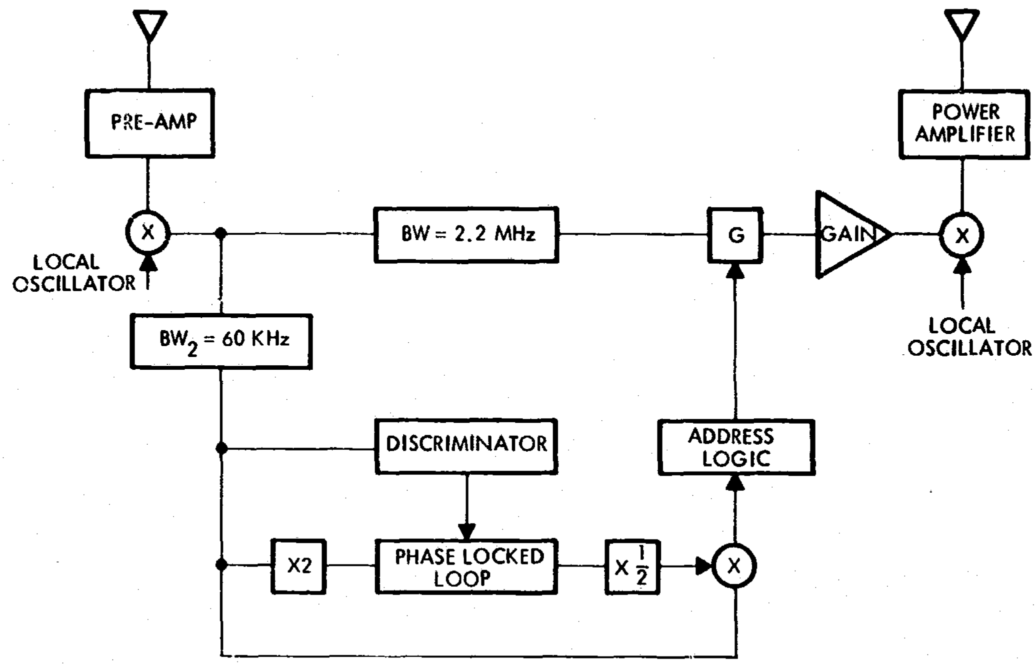


Figure 79. User Transponder for Digital Matched Filter

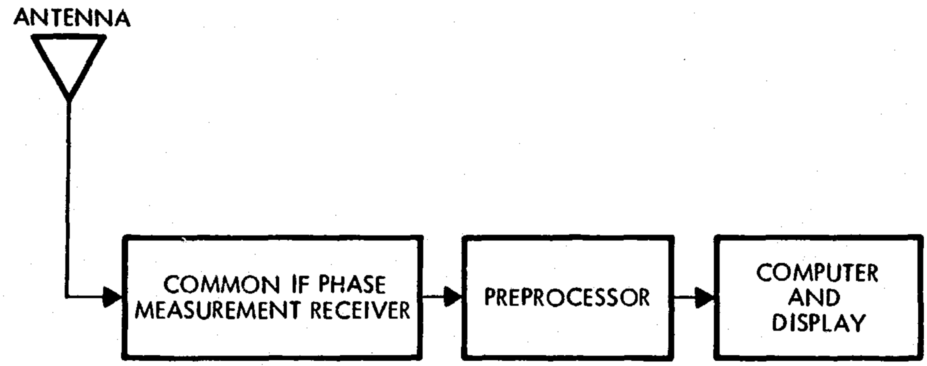


Figure 80. User Equipment for Passive Interferometer

The generic form of the user equipment for the interferometer is quite similar to the user equipment for the passive ranging concept. Since the measurement of phase difference between the signals transmitted from the satellite interferometer does not involve as much complexity as the code acquisition/correlation process associated with the BINOR passive ranging system, it appears that the user equipment associated with the interferometer will be slightly less expensive than that associated with the passive ranging concept. The passive interferometer, like the passive ranging concept, could operate without a general purpose computer by expressing the user location in terms of a polynomial expansion in the measured variables made about a reference point.

5.6.6 User Equipment for the Active Range and Interferometer Concept

The user equipment for the active range and interferometer concept receives a ranging signal from a satellite, decodes the user address information, and retransmits the appropriate information and a CW signal whose duration will be of the order of 10 milliseconds. A CW signal is used for making angular measurements with a receiving interferometer based in the satellite. Consequently, the only difference between the user equipment associated with an active range concept and an active range and interferometer concept is that the latter transmits a CW signal from the user in addition to the ranging signal. Consequently, there will be a negligible difference in the user equipment for the latter concepts from the point of view of cost comparison.

It is worth mentioning that the requirement for a pulse compression delay line to detect the user addressing pulses in the pulse compression active ranging system increases the cost of this unit considerably. It appears that this is a major cause for the difference in cost in the pulse compression implementation and the digital matched filter implementation of the active ranging concept. In the event that further work on the pulse compression mechanization is undertaken for the active ranging concept, it would be desirable to investigate methods of eliminating the requirement for the pulse compression delay line in the user-receiver.

5.7 REFERENCES

1) "Study of a Navigation and Traffic Control Technique Employing Satellites," TRW Systems Contract NASW 12-539, December 1967.

2) L.J. Mitchler, "Active Ranging Navigation Satellite System," TRW Systems IOC 7224.11-2, March 1968.

3) L.J. Mitchler, "Capacity of an Active Ranging System," TRW Systems IOC 7222.6-235, February 1968.

4) R.A. Maag, "Implementation of the Active Ranging System, ERC Navigation/Traffic Control Satellite Mission Study," TRW Systems IOC 7224.10-7, 8 April 1968.

5) W.G. Meyers, "Final Report, User Equipment Study, Active Ranging NAVSAT," TRW Systems IOC 7243.8-2, 3 April 1968.

6) "Navigation Satellite System," Westinghouse Electric Corporation, Contract NASW 785, January 1964.

7) D.M. Jacob, "Analysis of Navigation Satellite Concept No. 4," TRW Systems IOC 7243.2-163, January 1968 (rough draft).

8) P.R. Schultz, "The Fan Beam Navigation Satellite Concept," TRW Systems IOC 7223.2-264, February 1968.

9) H.T. Ekstrand, "Coverage Analysis for Navigation/Traffic Control Satellite Mission Study," TRW Systems IOC 3414.1-81, January 1968.

10) K. Gould, "Ground Station Implications for Various Navigation Satellite Concepts," TRW Systems IOC 7222.6-252, April 1968.

11) "Navigation/Traffic Control Satellite Mission Study," TRW Systems Group Proposal No. 09778.000, 5 June 1967.

12) A.J. Mallinckrodt, " Preliminary Description of the Big-Omin Nav.Sat.," TRW Systems IOC 7222.1-226, 23 May 1967.

13) A.J. Mallinckrodt, "Big OMNI Receiver and Data Extraction," TRW Systems IOC 7222.1-390, 3 January 1968.

14) "Fan Beam Navigation Satellite Study," Philco WDL Division Report WDL-TR-2962, 13 July 1966.

15) L.M. Keane, "Recent Progress in Navigation Satellites," Proceedings of the ION National Air Meeting on Supersonic Navigation, 15-16 November 1967, Seattle, Washington.

16) A.J. Mallinckrodt, "Initial Considerations for System No. 7 (Long Baseline Interferometer)," TRW Systems IOC 8800.3.3.3, 23 April 1967.

17) M.I. Skolnik, Introduction to Radar Systems, McGraw-Hill Book Co., 1962.

18) D.C. Hogg and W.W. Mumford, "The Effective Noise Temperature of the Sky," Microwave Journal, Vol. 3, pp. 80-84, March 1960.

19) G. Wong, "Wide Angular Coverage Circularly Polarized Antenna for NAVSAT Applications," Presented at the National Aerospace and Electronic Conference (NAECON 1968), Dayton, Ohio, May 1968.

20) D.A. Conrad and S.Y. Itoga, "The Role of Correlations in Navigation Satellite Error Analysis," to be presented at the AIAA Specialists Conference, September 1968, in Jackson, Wyoming.

21) A.J. Mallinckrodt, "Attitude Control Limits for Interferometric NAVSAT," TRW Systems IOC 7222.1-401, 10 January 1968.

22) L.J. Mitchler, "Preliminary TRW Active Ranging System Error Analysis," TRW Systems IOC 7224.11-9, 9 April 1968.

23) A.J. Mallinckrodt, "Propagation Errors for Interferometric NAVSAT's," TRW IOC 7222.1-402, January 1968.

24) L.J. Mitchler, "VHF Active Ranging Error Analysis," TRW Systems IOC 7224.11-20, 5 June 1968.

25) J.J. Stiffler, "Rapid Acquisition Sequences," IEEE Transactions on Information Theory, Vol. IT-14, No. 2, pp 221-225, March 1968.

26) L.J. Mitchler, "Passive Ranging Error Analysis," TRW Systems IOC 7224.11-14, 9 May 1968.

27) S.Y. Itoga, "Results of Error Analysis for Navigation/Traffic Control Satellite Mission Study," TRW Systems IOC 3412.8-116, 10 April 1968.

28) S.Y. Itoga, "Effects of Longitude Spread on Navigation Accuracy with Synchronous Equatorial Satellites," TRW Systems IOC 3412.8-118, 16 April 1968.

29) E.D. Perry, "Navigation Receiver Cost Comparison," TRW Systems IOC 7322.02-04, 23 April 1968.

30) J.R. Klauder, et al., "The Theory and Design of Chirp Radars," Bell Systems Technical Journal, Vol. 39, pp. 745-808, July 1960.

31) A.J. Mallinckrodt, "A High Dispersion Digital Pulse Code System," TRW Systems IOC 7222.1-372, 7 December 1967.

32) H. L. Mork, "Preliminary Attitude Control Investigation for the Navigation Satellite," TRW Systems IOC 68.7236.2-33, 30 April 1968.

33) J.C. McMunn, "Navigation Satellite Boom Vibration Analysis," TRW Systems IOC 68-3343.5-16, 26 February 1968.

34) L.J. Mitchler, "Interferometer Error Sources," TRW Systems IOC 7224.11-11, 9 April 1968.

35) W.M. Holmes, Jr., "Accuracy of Satellite Interferometer Navigation Systems," TRW Systems IOC 7323.4-104, 8 April 1968.

36) M.S. Stone, "Error Analysis in Common IF Phase Measurements," TRW Systems IOC 7323.2-221, 14 February 1968.

37) "Study of Satellites for Navigation," General Electric Co. Report, Contract NASW-740, February 1964.

38) P.R. Schultz, "Comparison of Accuracy of Various Satellite-Aided Navigation Techniques," TRW Systems IOC 7223.2-263, 8 April 1968.

39) A.J. Mallinckrodt, "NAVSAT Error Program-Relation Between Various Measurements," TRW Systems IOC 7222.1-328, 1 November 1968.

40) F.M. Holmes, "Navigation Satellite Constellations Study," TRW Report No. 09424-6001-T000, 14 November 1967.

41) A.J. Mallinckrodt, "Propagation Errors for Interferometric NAVSAT's," TRW Systems IOC 7222.1-402, 16 January 1968.

42) P.R. Schultz, "Comparison of User Software for Passive Navigation Satellite Concepts," TRW Systems IOC 7224.11-13, 15 April 1968.

PRECEDING PAGE BLANK NOT FILMED.

6. SPACECRAFT SUBSYSTEM DESIGN TRADEOFFS

6.1 GENERAL

Three particular spacecraft subsystem design tradeoffs, i.e., attitude control system, antenna, and solar array received special emphasis in the study and are treated in the following sections. The resulting satellite configuration is then described and a weight statement is itemized in Section 6.5.

6.2 ATTITUDE CONTROL SYSTEM (ACS) SELECTION

The ACS choice is a function of spacecraft power requirements and overall weight, the required attitude determination accuracy, the orbital configuration, and the payload antenna pointing requirements (including number and size of payload antennas). The total dc power requirements for satellite operation will be on the order of 1400 watts; satellite weight is on the order of 7000 lbs.

In the following paragraphs the question of spin versus three-axis stabilized spacecraft configurations is addressed. The candidate stabilization choices are described and satellite system considerations are discussed. It is concluded that the three-axis stabilized configuration is far superior for the required missions. Satellites in both types of orbits should be three-axis stabilized; satellites in synchronous equatorial orbits do not require full two-axis control of solar paddle surfaces, and the control subsystem should utilize pitch momentum wheels to eliminate the requirement for yaw sensing. The NTC satellites in inclined orbits should utilize full three-axis stabilization with mass expulsion and perform periodic yaw turns to achieve solar paddle sun orientation.

6.2.1 Three-Axis Stabilization

6.2.1.1 Description

In the fully active spacecraft attitude stabilization technique (mass expulsion only), earth or celestial references are required for each axis of control. Control torques are provided by mass expulsion gas jets; control accuracies better than 0.1 degree are possible. An attitude sensor system measures the displacement of body axes from the reference axes. The axes are defined such that the spacecraft yaw axis would be along the local vertical, the pitch axis is maintained normal to the spacecraft sun line (accomplished by periodic yaw turns), the roll axis forms a mutually orthogonal set. For spacecraft in synchronous equatorial orbit, the pitch axis is maintained perpendicular to the orbital plane and the roll axis in the direction of travel. The attitude error angles (roll, pitch, and yaw) are converted into electronic signals by the sensor electronic unit; pulse modulators issue command pulses to turn on thrustors for a time duration proportional to the attitude error magnitude. The spacecraft will normally oscillate about the desired attitude within a pre-selected dead zone.

A variation of the three-axis stabilization with mass expulsion is the use of a reaction wheel to provide basic gyroscopic stiffness; the wheel spin vector is oriented perpendicular to the orbital plane. Two-axis earth horizon sensors continue to provide roll and pitch attitude information to the control system but the spacecraft pitch orientation is controlled by means of reaction torque from the wheel drive motor. The earth-orbital kinematics causes the roll and yaw attitude errors to interchange in a sinusoidal manner with respect to orbit position, allowing the attitude control for both the roll and yaw channels to be accomplished by a single set of jets. The accumulation of pitch momentum due to secular type disturbance is corrected by means of jets operating in an on-off mode. No separate yaw sensor is required in this attitude control technique.

6.2.1.2 Satellite System Considerations

A major advantage associated with the three-axis stabilized spacecraft configuration is the increased power generation efficiency (versus spin-type) for power requirements on the order of 1 kilowatt. The spinner requires three times the amount of solar cells required for a comparable single axis controlled solar array. Spacecraft trade analyses have been performed to determine the power generation efficiency as a function of overall spacecraft gross weight. Typical solar power versus satellite weight curves are shown in Figure 81 for communications satellites. It may be seen that below the cross-over point of approximately 550 pounds, spin stabilized spacecraft are more efficient (total satellite weight) in solar power generation than a comparable three-axis stabilized; however, for solar power requirements on the order of 1 kilowatt as required by this mission, three-axis stabilized spacecraft are much more efficient.

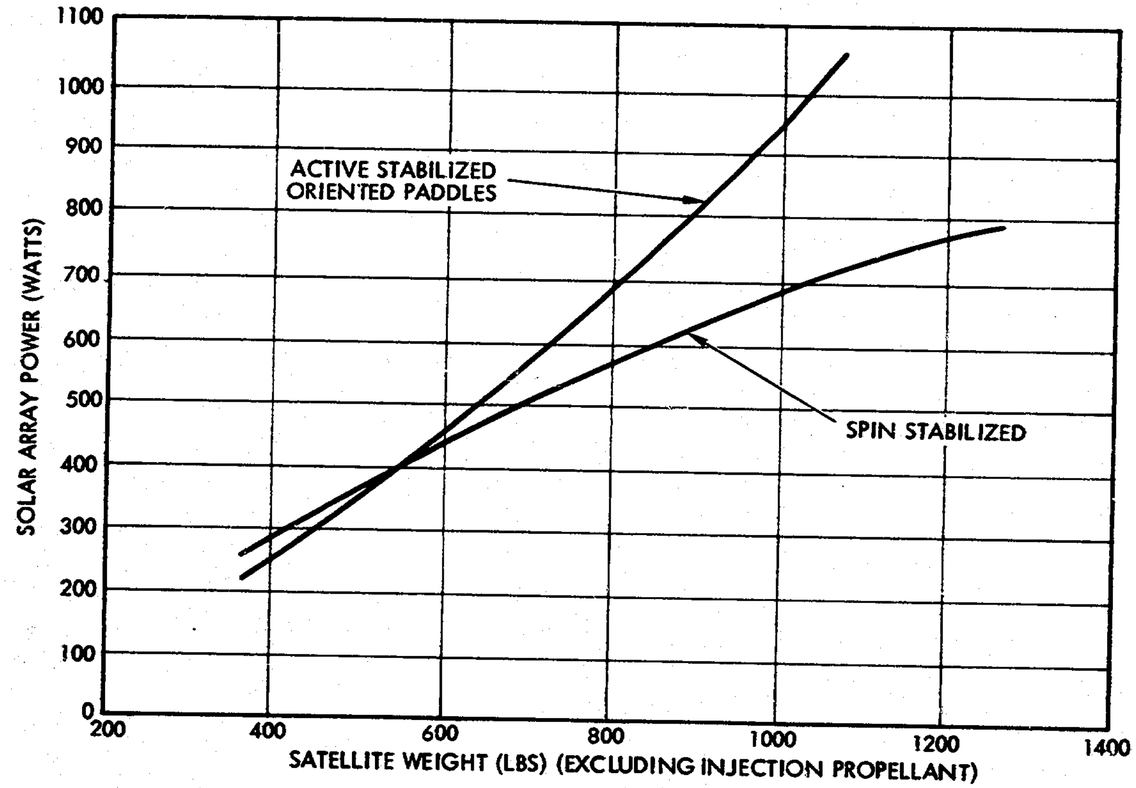


Figure 81. Solar Array Power Versus Satellite Weight—Commercial Communications Satellites (Synchronous Equatorial Orbits)

To achieve 1 kilowatt of dc power at beginning of life, a spin stabilized spacecraft in synchronous equatorial orbit would require a cylindrical shell approximately 10 feet in diameter and 10-feet tall. This presents a problem when the required launch vehicle has a 5-foot diameter shroud; alternatively an OAO shroud (10-foot diameter) may be used with accompanying payload degradation.

In addition, the spacecraft configuration is extremely flexible, allowing increase of solar cell area with minimum modification and positioning of spacecraft antennas with ease. Other advantages are that a yaw sensor is not required and the wheel bearings are in an enclosed environment (as opposed to the dual spin configuration). If a pitch wheel is used, however, the control system weight is greater than for a comparable active three-axis system.

6.2.1.3 Synchronous Equatorial Orbits

Single axis control of solar paddles is adequate for spacecraft in synchronous equatorial orbits since the maximum spacecraft-to-sun angle is 23 degrees, increasing (as opposed to full orientation) required solar cell area only by a factor of 1.1. A three-axis stabilized spacecraft with single-axis-controlled solar paddles would require a total solar cell area of approximately 100 ft^2 to generate 1 kilowatt at beginning of life. Accordion fold-out or roll-out thin film arrays can be used very effectively with three-axis stabilized techniques, reducing overall power subsystem weights. Since only single axis control of the solar arrays is required, it is recommended that a three-axis stabilized with momentum wheel technique be used, eliminating the requirement for a suitable yaw sensor.

6.2.1.4 52.5 Degrees Inclined Orbits

A three-axis stabilized satellite configuration is ideal for inclined orbits since full two-axis control of the solar paddles is a necessity for efficient power generation. Full solar paddle sun orientation can be obtained by a combination of single axis control of the solar paddles (rotation about the solar paddle axis) and periodic turns of the spacecraft about its yaw axis. This method of obtaining full sun orientation does not allow the use of a combination pitch wheel/mass expulsion stabilization system; yaw sensing is now required. Sun sensors could be used for attitude determination during most of the orbit, with an interferometer system used to maintain antenna pointing during eclipse periods and during those periods when the spacecraft sun line is within the effective yaw sensing dead zone. Alternatively, star trackers could be used during these periods. One disadvantage of the yaw turn approach to achieve effective sun orientation is an increased burden on antenna pointing requirements; the antenna must remain pointed at the required terrestrial location during (and after) spacecraft yaw turns. An alternative but undesirable approach would be full two-axis control of the solar paddles themselves; this results in increased complexity and weight of solar paddle control equipment accompanied by decreased reliability. The proposed solution for Configuration B is to replace the pitch wheel with a yaw wheel. While this change increases gas consumption somewhat, the additional gas required over a 5-year period is still less than the weight of an additional wheel. Consequently, it appears desirable to delete the pitch wheel. The yaw wheel will be torqued at some constant rate (variable with the season) to insure full solar array orientation capability.

6.2.2 Dual Spin Stabilization

6.2.2.1 Description

A dual spin spacecraft configuration has an axisymmetric rotor attached by bearings to an asymmetric nonspinning structure. The passive wobble damper, antennas, and communications subsystems could be located on the despun platform, the solar cells are mounted on the outer portion of the spinning cylinder. The stabilization momentum bias is provided by the satellite body spinning at a fixed rate. Earth sensors provide spin rate reference and pitch reference information for orientation of the despun platform. The earth sensor information is used in conjunction with the reference gating-logic to provide control of the spin axis orientation. Control accuracies on the order of 0.1 degree are possible with the dual spin approach. This approach is inherently less complex than three-axis stabilization, but the latter can be designed for comparable reliability.

6.2.2.2 Satellite System Considerations

One of the most undesirable features associated with the dual spin stabilization approach is the inefficient power generation for power requirements of approximately 1 kilowatt as is necessary for this mission. The large structural and solar array weights result in significantly less communication capacity than systems using oriented arrays. For a dc requirement of 1 kilowatt, the spacecraft configuration would be such as to require large, heavy fairings (i.e., OAO). An advantage is the use of relatively simple horizon sensors and the elimination of the requirement for a solar array drive system (body-mounted solar cells).

6.2.2.3 Synchronous Equatorial Orbits

The spinner is oriented such that the spin axis is perpendicular to the orbit plane so that, when the antenna platform is despun, the antennas are earth oriented. A cylindrical solar array forms the outside of the satellite, producing volumetric constraints for high power generation. Signals from IR earth sensors are used to control the antenna platform orientation; no yaw sensor is required. As mentioned above, the spinner requires three times the amount of solar cells required for a comparable single axis controlled solar array.

6.2.2.4 52.5 Degree Inclined Orbits

Spin stabilization is an advantage primarily when the spacecraft are oriented such that the spin axis is perpendicular to the orbital plane. For satellites in highly inclined orbits, this presents a severe reduction in power generation efficiency: the spacecraft sun line (worst case) can be as high as $\pm(23^{\circ} + i)$. For the case of a 52.5 degree inclined orbit, the spacecraft sun line can be as high as 75.5 degrees, reducing the effective solar power by a factor of approximately 4.8 (solar cells mounted on the periphery of the spinner cylinder). The power generation efficiency can be increased by producing an omnidirectional solar cell configuration, but for power requirements on the order of 1 kilowatt dc, a spinner in highly inclined orbits is not effective. One possible alternative is to orient the spin axis of the satellite perpendicular to the plane of the ecliptic, thus providing comparable effective solar cell area as a spinner in synchronous equatorial, but the spacecraft directional antennas must nutate periodically to maintain pointing at a desired terrestrial location.

6.3 ANTENNA CONFIGURATION SELECTION

The antenna system, because of the large antennas and limited dynamic envelope of the Agena type fairing (about 59-inch diameter) is of major importance in its effect on the configuration. Weight, performance, reliability, and the requirement to leave a clear field of view for the horizon scanner system were the constraints for selecting the antenna arrangement.

Four types of antenna configurations were considered: (a) an antenna that is fully gimballed (to allow command pointing), stowed upright, and deployed to an operational position; (b) configuration that is not deployable, but could be adjusted to the desired pointing angle before launch; (c) configuration that is fully deployable from a furled condition; and (d) a configuration that is a combination of the (a) and (c). The first antenna configuration meets all the design constraints. It gives the most freedom in the location where the antenna could be stowed and where it could be deployed. This minimized the solar pressure unbalance over the subsequent configurations. It also permitted a nearly 180 degree clear view for the horizon scanners except for the antenna deployment arms when the small 36-inch diameter antenna is deployed. However, deployment of both antennas requires heavier antenna support systems, more electrical power, heavier deployment mechanisms, and suffers in reliability.

A nondeployable but gimballed antenna, or one that is adjustable before launch to a particular setting, requires that some provision be found for obtaining a clear view for the horizon scanners. Horizon scanners of the advanced OGO type require two units, each with a 180 degree field of view and at approximately right angles to each other. It was proposed that a new unit be developed incorporating four or more scanning heads, and that the unit be placed on the antenna feed. Apart from the development problems which could be met, the unit would require a ±8 degree adjustable base, the mounting must be rigid enough to provide a vibrational environment comparable to a body mounted unit, and heaters and insulation must be used to keep it within defined temperature limits. The scanner's accuracy is rapidly degraded at limits that are far less than the extremes encountered in space. The units estimated weight of 14 pounds made the vibrational constraint (due to the internal oscillating mirror support) very severe when mounted on the antenna feed. This antenna concept was therefore abandoned.

The 66-inch diameter communications antenna cannot be contained in a 59.5-inch dynamic fairing without either using an unfurlable antenna or hinging two sides of the antenna and extending them when the antenna is deployed. If the antenna sides are folded aft of the face, the antenna is usable at a reduced area in the event of deployment failure. It is also possible to use an unfurlable concept for the complete antenna. Several such concepts are being developed at the present time. These are very lightweight designs but at the present time their reliability and performance have not been established.

The fourth choice is a combination of a deployable antenna in one plane only that has either hinged sides or a furlable perimeter to reduce the diameter to launch requirements. This concept is the most attractive. It was found that deploying the antenna with an elbow joint did limit where the antenna could be deployed thus increasing the solar pressure unbalance slightly over the first concept. This concept also requires an adjustment feature where the antenna wrist type rotation is preset before launch to any angle of ±8 degrees. To accomplish this wrist type rotation, an adjustment feature was designed consisting of two facing flanges with a sleeve bearing extending through both flanges for continuity. By a system of holes in the flanges, the two faces can be rotated in 1/4 degree increments up to 8 degrees and then bolted together at the selected angle.

Several types of deployment mechanisms were considered that are compared in Table 29. The ball bearing screw actuator was selected for its simplicity, low weight, and for the capability of a ±8 degree adjustment by simply resetting the actuator limit switches. This type of actuator together with the flange rotation gave the required prelaunch adjustment.

The unfurlable antenna concept was applied to the outer rim of the antenna. This concept is very simple consisting of a series of contoured ribs fastened to a circumferential frame around the rigid part of the antenna and covered with aluminized mylar. The ribs, when released, deploy under their own strain energy to form the proper parabolic contour with the restraint of the aluminized mylar reflector surface.

6.4 SOLAR ARRAY SELECTION

During past years solar array design technology has undergone a gradual improvement with the goal of more power for less weight and storage volume. A monocoque structure with solar cells previously used has now yielded to a lighter weight fiberglass honeycomb array with a spar

Table 29. Comparison of Antenna Deployment Mechanisms

	Type	Weight	Reliability
1.	Ball Bearing Screw Actuator Permits easy ±8 degree adjustment. No hold down and release pyrotechnics required. Low cost development of motor to drive ball bearing nut required.	Low	High
2.	Gimbal-type Motor Drive Same as above except adjustment of ±8 degrees setting difficult without feedback position system. Moderate development cost.	Medium	Good
3.	Wobble Gear with Cable and Drum Requires hold down and pyrotechnic release system. No easy ±8 degree adjustment. Moderate development cost.	High	Good
4.	Pyrotechnic Thruster Drive Requires a ball lock on each end of travel, and a pyrotechnic thrust cylinder with dual squibs for thrust with a damper action at end of stroke. Sophisticated development.	Low	High
5.	Compression Spring Actuator with Internal Damper This would require a hold down system with pyrotechnic release. Development of spring and damper at low cost but above No. 1 above.	Low	High
6.	Tension Spring Actuator and Separate Damper Same as No. 5 but two springs are required for reliability equivalent to No. 5.	Medium	Good

stiffener. Recently, thin film roll-up type solar arrays were proposed, but the low efficiency (about 50 percent of silicon cells) led to new concepts of using silicon cells on a flexible substrate.

Several companies, including TRW, have proposed novel new concepts for these lightweight solar arrays. TRW Systems Group has compared these concepts and configured a design based on these studies. This review was published as "Silicon Cells Adapted to Thin-Film Solar Array

Concept", (SCATSAC) in Reference 1. Based on this and continuing studies, a specific solar array design for the Navigation Traffic Control Satellite is shown in Figure 82.

The design utilizes 0.008 thick silicon cells protected by bonded glass covers mounted to a three-mil Kapton substrate. The glass covered cells are stored face to face on zee folded panels during launch. A three-mil Kapton double hat section forming a circular tube is used to stiffen both array edges. Two of these formed sections are also used to stiffen the center of the array. These all fold flat for launch storage. Tests establishing the feasibility of this scheme have been completed by TRW.

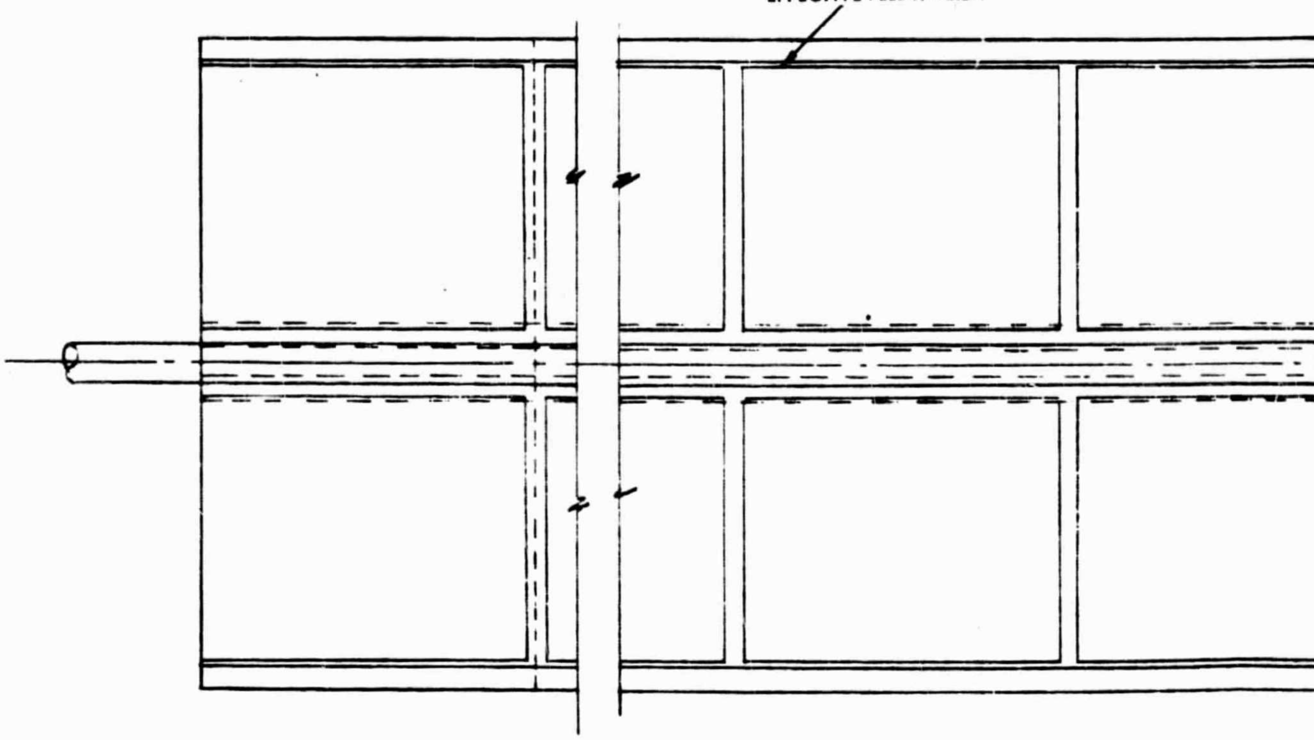
The design utilizes a single center boom supporting the array from a tubular crosspiece at the end of the boom. Several types of boom cross section have been considered, but the double hat section has the best bending and torsional properties. This high torsional resistance resists twisting of the array. The boom can be made up of multiple sheets to any total thickness required with the sheets formed into hat sections and the nested sections spot welded at the flange as shown in Figure 82. The double hat section can be deformed into a flat sheet and rolled on a drum. The flattened tube reforms to its original shape when unwound and the pressure is released. The same cross section is used in the Kapton tubes used for stiffeners. This type of boom requires a very short transition distance to be formed and thus permits a shorter extension mechanism than the bi-stem type commonly used.

Table 30 gives the various material densities, ρ, modulus of elasticities, E, and ratios of $E\rho$. There is little difference in the ratio of E/ρ for stainless steel and titanium. The vibration frequencies in CPS, f, were calculated for the three boom materials assuming the same weight of array as uniformly loading the different weight cantilever beams. The vibration was calculated using the formula from Reference 2.

$$f = \frac{3.52}{2\pi l^2} \left(\frac{EI}{m}\right)^{1/2}$$

where I is the moment of inertia, l is the length, and m is the mass per unit of length. The vibrations being nearly equal, the weights given in the table were the major factor in recommending titanium. The four Kapton

PRECEDING PAGE BLANK NOT FILMED.



Foldout #1

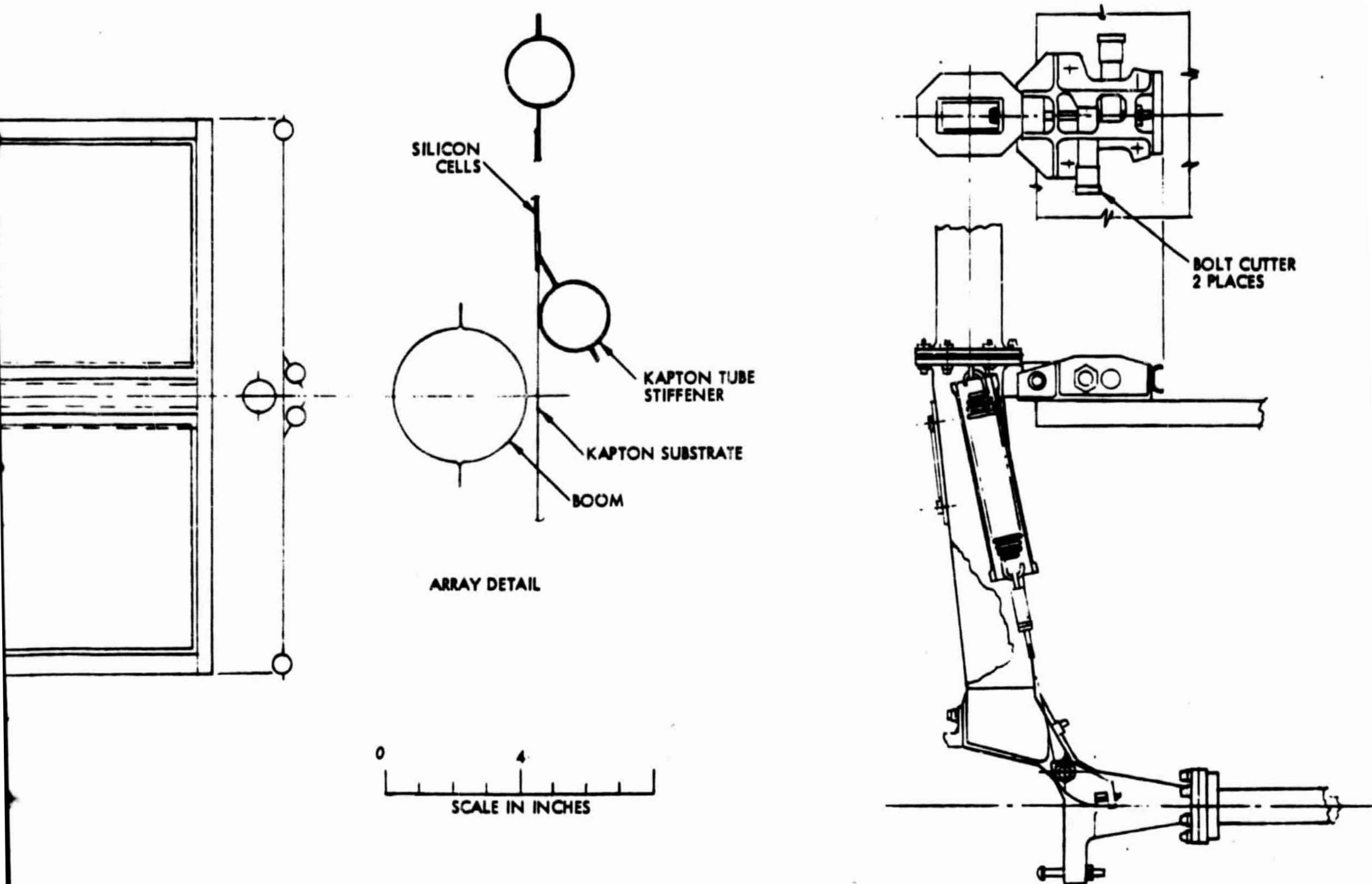


Figure 82. **Solar Array Detail, NTC Satellite (Configuration C)**

Foldout #2

PRECEDING PAGE BLANK NOT FILMED.

stiffeners on the array should also add to the panel stiffness but were not included in the calculations.

Thermal bending for the boom can be a significant problem, but proper coatings and perforations can be used to lessen the problem. The exterior is painted for high reflectance and the interior is painted black. Sunlight shining through the perforations is absorbed on the black interior and neutralizes the bending. All three of the materials would require this treatment of perforation and coatings. This factor, therefore, would not establish a material preference.

Table 30. Comparison of Boom Materials

Boom Material	Boom Wt.* (lb)	f* CPS	$E \times 10^6$ PSI	$lb/^{\rho} in^3$	$E/\rho \times 10^6$
Stainless steel	9.9	0.558	29.5	0.276	107
Titanium	5.85	0.430	16	0.163	98.2
Beryllium copper	10.6	0.435	19	0.297	64

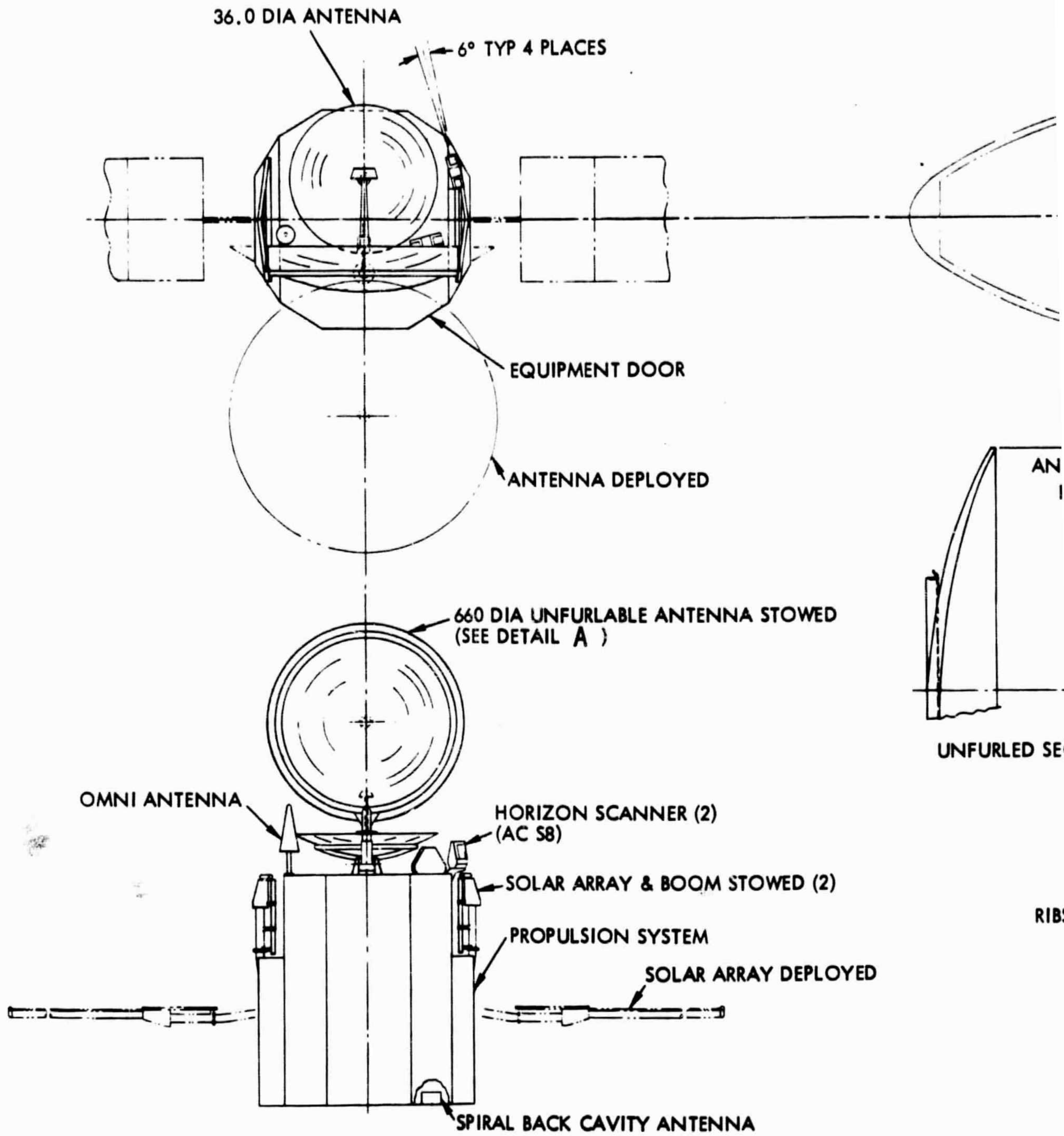
*Unpainted 410-in. long boom.

An estimated array weight is given in Table 31 based on SCATSAC weights. A further saving in weight is realized from the small storage volume required during launch that enables a shorter fairing and the absence of tiedown structure required to support the array. By the IOC date of 1975, substantial weight savings can be realized by using this design.

6.5 CONFIGURATION DESCRIPTION

As a result of the above tradeoff studies, the configuration shown in Figure 83 was developed. The large antenna is stowed upright and deployed 90 degrees to be operational. The center rigid part of the antenna is of a lightweight aluminum honeycomb. The rim frame for attachment of the aluminum wrap-around ribs adds rigidity to the antenna and anchors the mylar covering for the unfurlable outer antenna section. Ribs are spaced at 9 degrees. A strap is used to hold the ribs secured during launch and cut in two places by pyrotechnic strap cutters at deployment. A detail of

PRECEDING PAGE BLANK NOT FILMED.



Foldout #1

1

PRECEDING PAGE BLANK NOT FILMED.

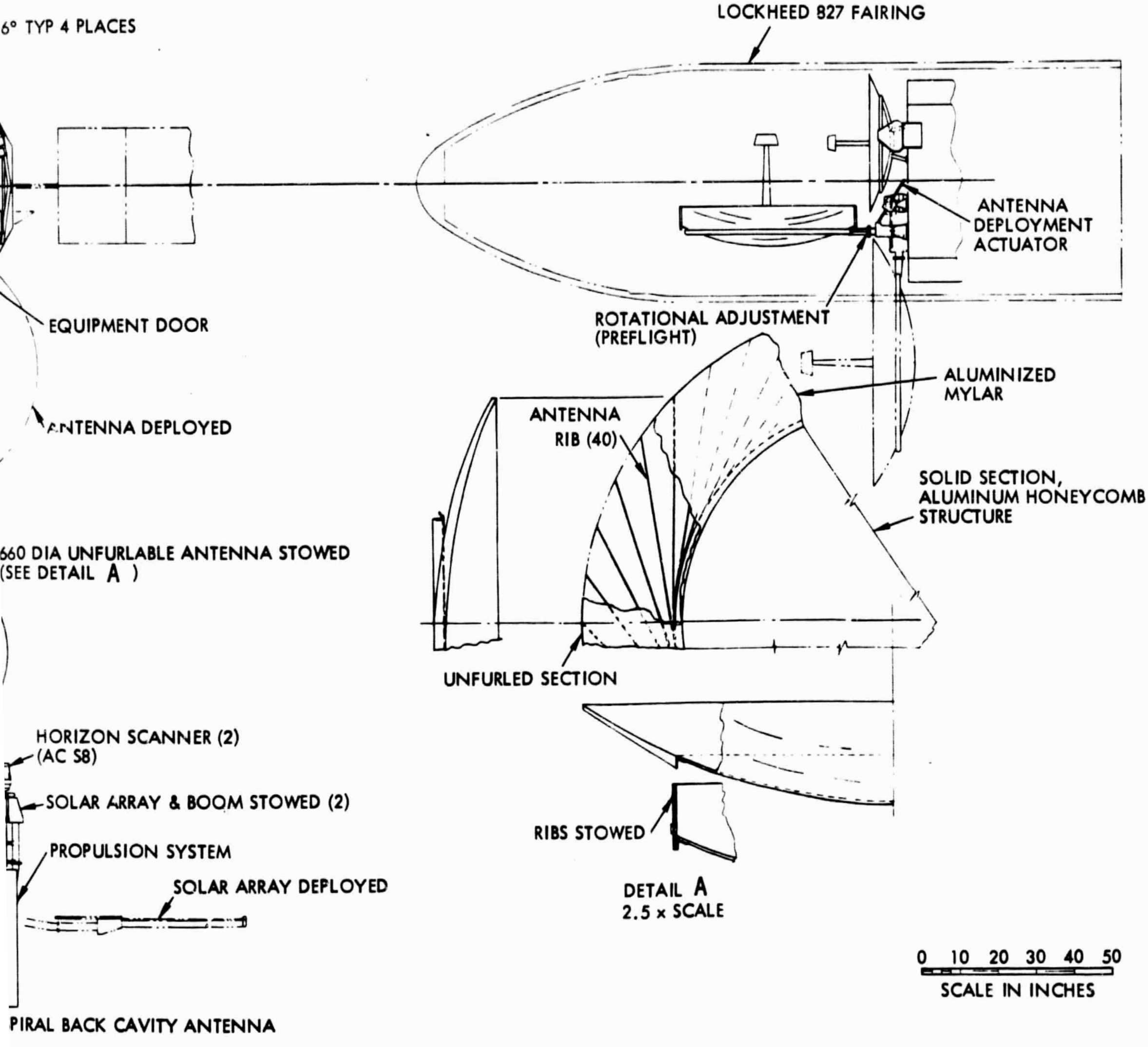


Figure 83. **NTC Satellite (Configuration C)**

Foldout #2

PRECEDING PAGE BLANK NOT FILMED.

Table 31. Weight Estimate for Zee Folded Array of 72 Ft^2

Array Weight

Item	Weight, (lb*)
Cells 2 x 2 cm x 0.008 thick	11.23
Cover glass (.003)	3.18
Connector tabs	0.49
Circuit boss	0.05
Filter adhesive	0.98
Mounting adhesive for cells	2.44
Cell modules	21.54
Total weight	39.91
Weight (lb/ft^2) =	0.319

Weight Summary

Array weight (72 ft^2)	22.98
Array stiffeners (4 of 3 mil Kapton)**	0.46
Substrate	2.67
Boom (Titanium)	5.
Actuator (estimate) (no motor)	5.
Hold down strap (0.75 x 0.020 x 0.067 (fiberglass) x 30 =	0.03
Pyrotechnic release	1.
Actuator hinge and latches (to rotate 90 degrees)	2.
Array storage support structure	0.75
Tee bar at end of array (1" OD x 0.020 x 30 Beryl + FTG)	0.26
Total array weight/side	40.15

*Based on 125 ft^2 from SCATSAC Study

**3 mil Kapton = 0.0313 lb/ft^2

this unfurlable antenna perimeter is shown in Figure 83. The large antenna is placed on the centerline of the satellite and rotates 90 degrees to deploy along this same centerline. The placement of the antenna shown allows a nearly 180 degree clear view for the horizon scanners that are placed at 90 degrees to each other. The 36-inch diameter antenna is attached by three tubular legs to the body of the spacecraft. The dish is constructed of honeycomb. A weight estimate for both of the antennas is given in Table 32.

Table 32. Weight Estimate for NTC Antennas

4-foot Diameter Solid Antenna	Weight, (lb)
9 mill face sheets (0.25) thick honeycomb = 0.18 lb/ft^{2*}	
12.56 ft^2 x 0.18	2.26
40 Ribs $\frac{0.5 + 1.5}{2} \times \frac{0.032}{10}$ = (48-66-inch dia deployed skirt)	3.07
Mylar	1.
Frame on antenna for rib attach:	
(1-1/2 + 1-1/2) 0.072 $\pi \frac{48}{10}$	3.25
Antenna stiff. ring 43 π (0.035 π 1.4) 1/10	2.08
Rivets attach. ribs to main dish	0.50
Antenna stem 2 in. OD x 0.065 = 4 lb/100, 4/100 (17) =	0.52
Antenna stem end ftg (6 in. long)	2.
Antenna feed 1.5	1.5
Antenna feed support 2 in. x 0.049 tube = 3 lb/100, 3/100 (26.5) =	0.80
Pyrotechnic strap cutter (2 places + wiring)	1.5
Collapsible antenna rim strap	0.25
Screw rod and motor for actuator (est.)	3.
Actuator ftgs on antenna and S/C	1.
Antenna ±8° adjustment provisions	1.
Antenna support ftg on S/C	1.
Contingency (10 percent of above)	2.47
Total	27.20
36-in. Diameter Antenna	
3-ft dia. honeycomb dish 0.18* x 7.06 ft^2	1.27
Antenna dish support (fixed)	1.
Antenna feed	0.75
Antenna feed support tube 1 in. OD x 0.049 = $\frac{2.5}{100}$ $\frac{2.5}{100}$ x 14	0.35
10 percent contingency	0.33
	3.70

*Jupiter pioneer antenna

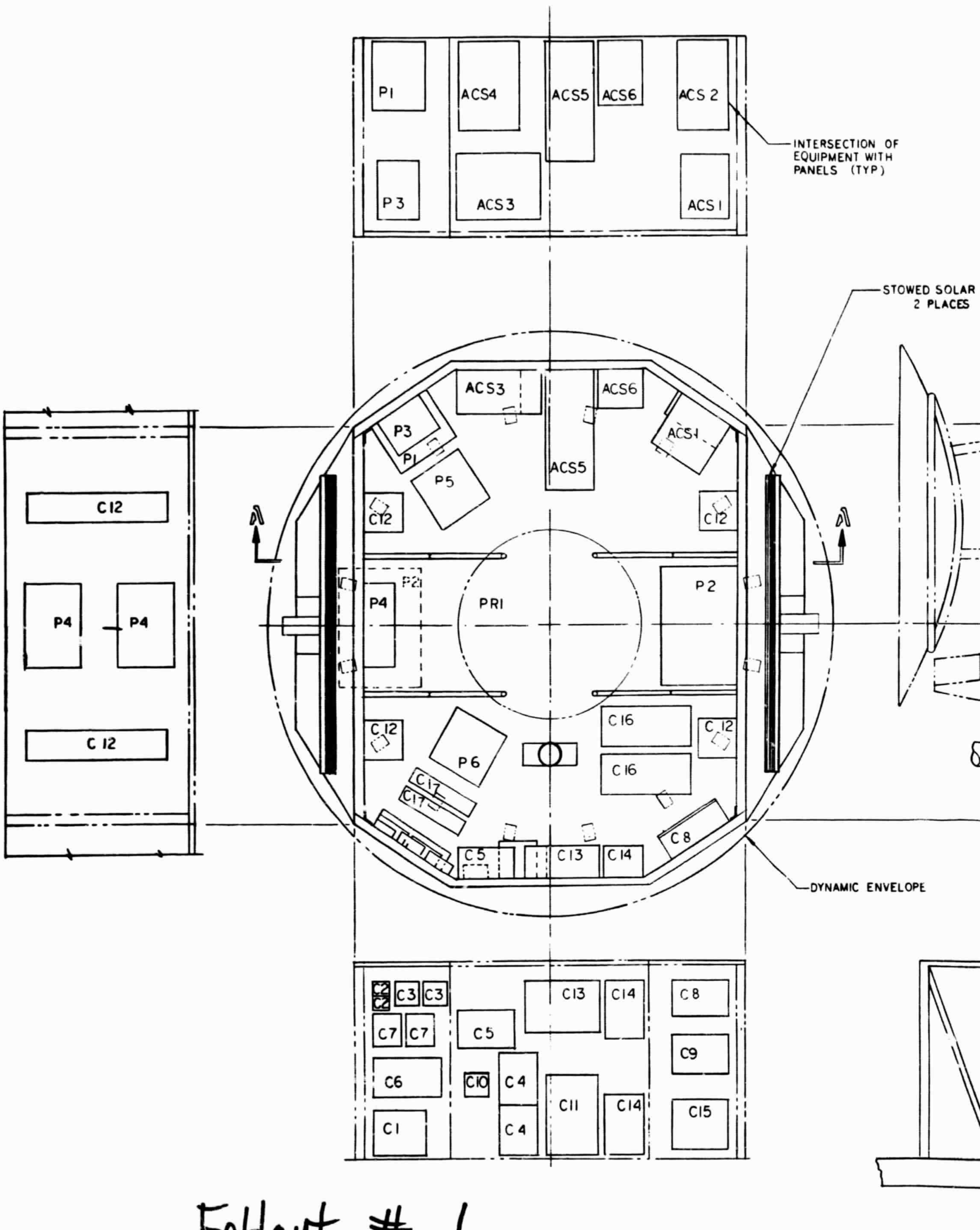
Thermal cooling of the spacecraft equipment is also an important consideration. Only the sides of the satellite facing the arrays are without sun exposure. High heat dissipation units must therefore be mounted on these surfaces. The entire external area must be covered by louvers or insulation except for sensors, jets, etc.

The shape of the propulsion system is best enclosed by a 12 sided polygon. This cross section is continued above the propulsion section for equipment storage except for an area on each side left for stowage of the solar arrays. The short satellite can be enclosed by the Lockheed 827 lightweight fairing as shown in the figure.

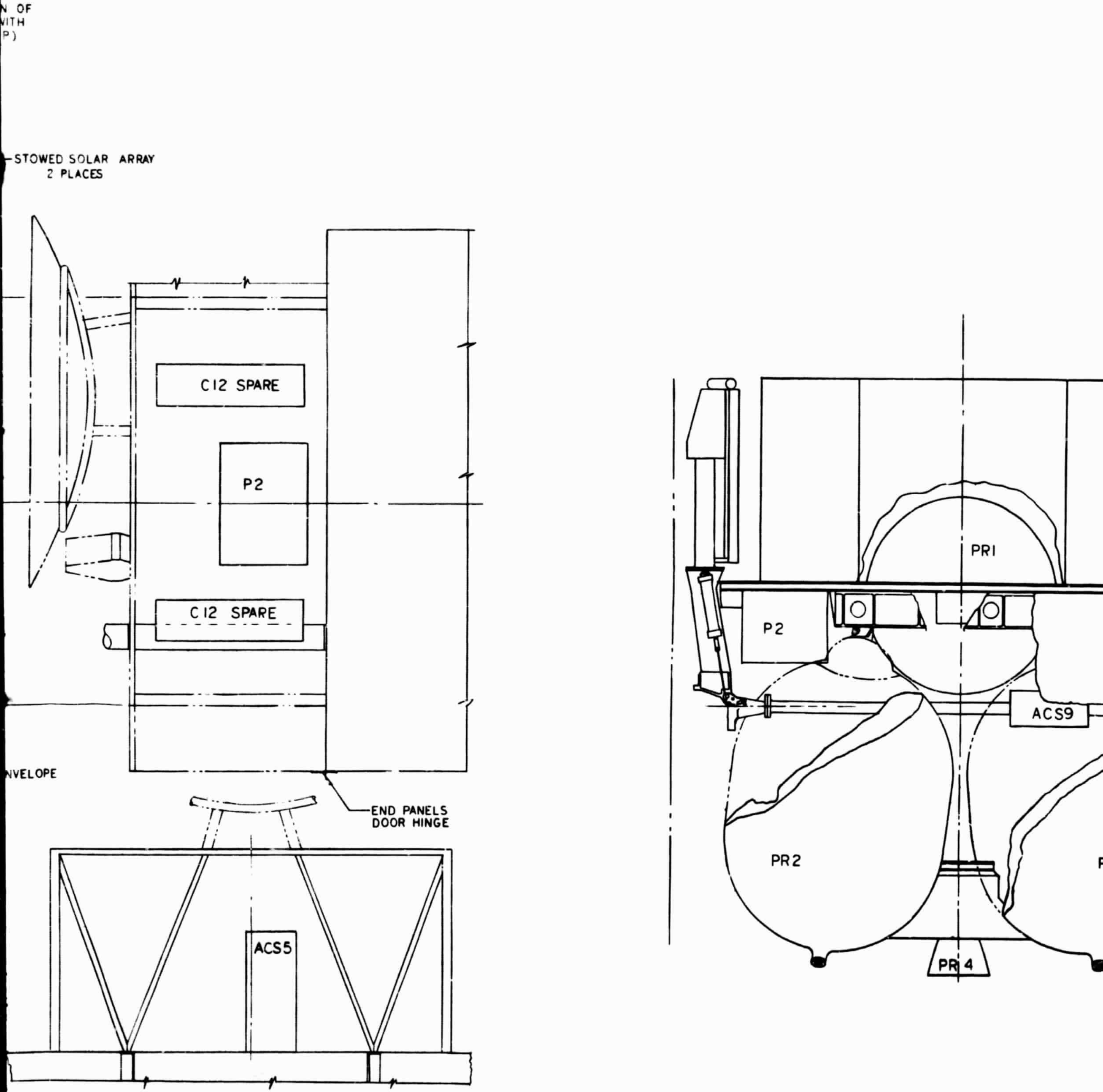
Figure 84 furnishes further details of the satellite and an inboard profile of the propulsion subsystem. Some equipment items identified by the code given in Table 33 are placed on a bulkhead above the propulsion subsystem. This bulkhead can be perforated as required to allow heat interchange between the propellant and equipment. Two batteries and some equipment units associated with the propulsion system are mounted below the bulkhead. These units aid in preventing propellant from freezing. The bulk of the equipment is mounted above the propulsion subsystem flat against the exterior panels for the best cooling. The panels facing the solar arrays are held in place by two internal aluminum truss assemblies. These also support the top panel, the small antenna, horizon scanners, and other external top mounted equipment. The end panels above the propulsion system are hinged to provide access to the equipment. Units of adjacent equipment are located on the basis of minimum length connecting harness runs. Sufficient room is left between units for the connecting harness.

A detail of the hinge mechanism for deploying the solar array is shown in Figure 82. The drum storage unit for the solar array boom is attached to the solar array hinge arm. The array deployment is initiated by the redundant bolt cutters shearing the tie down bolt and allowing the spring mechanism to deploy the arm. After the arm is deployed, the array can be extended.

PRECEDING PAGE BLANK NOT FILMED



Foldout # 1


N OF
VITH
P)
STOWED SOLAR ARRAY
2 PLACES
C12 SPARE
P2
C12 SPARE
NVELOPE
END PANELS
DOOR HINGE
ACS5
A-A
PR1
P2
ACS9
PR2
PR 4

Foldout #2

1

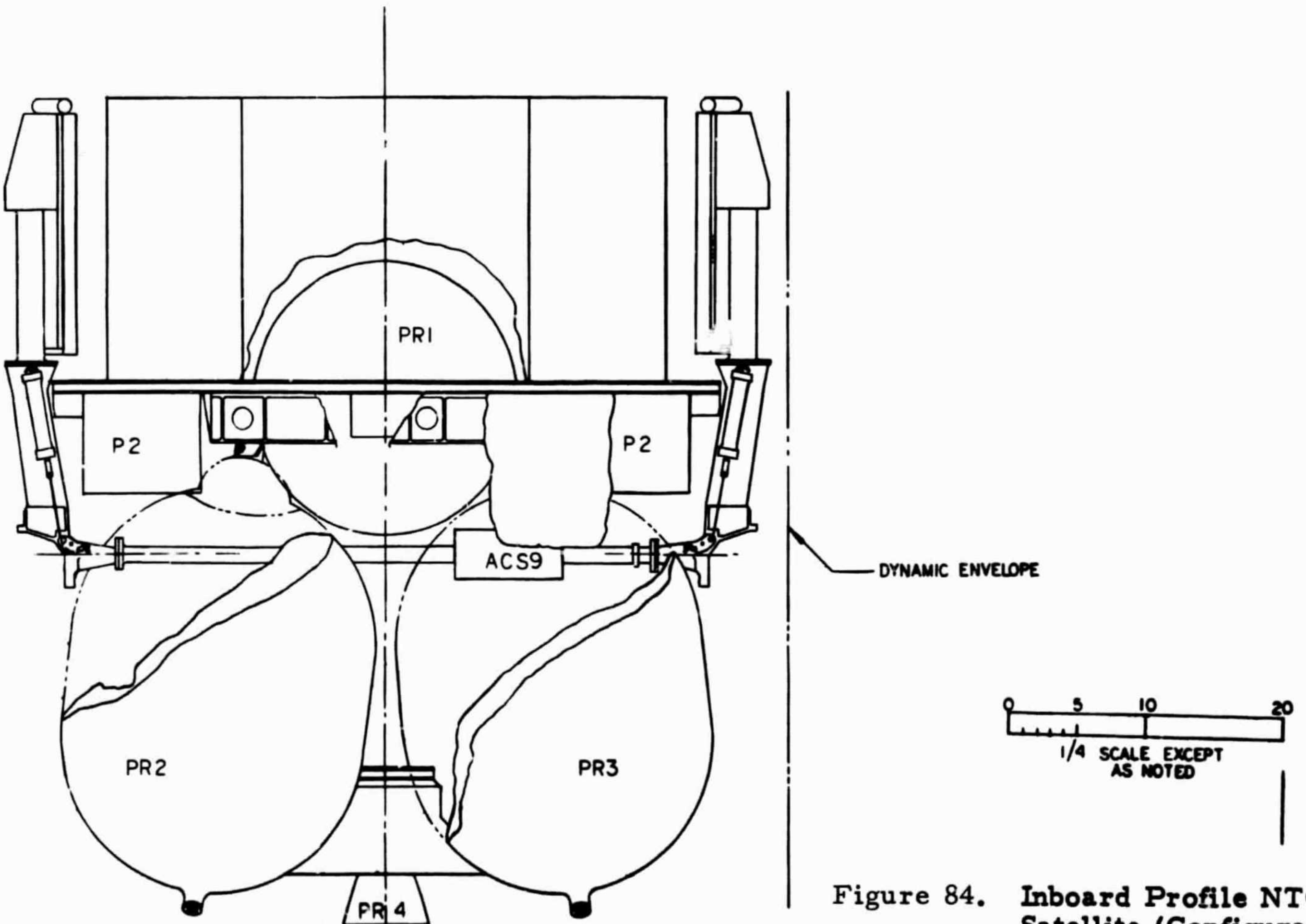


Figure 84. **Inboard Profile NTC Satellite (Configuration C)**

Foldout #3

PRECEDING PAGE BLANK NOT FILMED.

Table 33. Navigation/Traffic Control Satellite (Equipment Identification Code)

C1	Diplexer (S Band)
C2	Hybrid
C3	Command RCVR
C4	Command decoder
C5	Telemetry transmitter
C6	Telemetry encoder
C7	RCVR selection
C8	L-band diplexer
C9	Freq. multiplexer (L Band)
C10	Isolator
C11	Transmitter
C12	TWT and power supply
C13	Receiver
C14	Solid state power amplifier
C15	Freq. synthesizer
C16	Ref. oscillator
P1	Power control unit
P2	Battery
P3	Central DC/DC converter
P4	Shunt assy
P5	Electrical integration unit
P6	Telemetry integration module
ACS1	Gyro. ref. assy
ACS2	Sensor electronics
ACS3	Control electronics
ACS4	Actuation electronics
ACS5	Reaction wheel
ACS6	Reaction wheel electronics
ACS7	Sun sensor assy
ACS8	Horizon sensor assy
ACS9	Solar array drive
PR1	Pressurant (N) tank
PR2	Oxidizer (N_2 0_4)
PR3	Fuel (MM_H)
PR4	Engine assy

6.6 REFERENCES

1. Dillard, Paul, "Silicon Cells Adapted to Thin-Film Solar Array Concept (SCATSAC)", No. 68-3524 2-16, 7/16/68, Pg 228-301.

2. Harris, Cyril a... Crede, Charles, "Shock and Vibration Handbook", Volume 1, McGraw Hill, 1961.

APPENDIX A

SINGLE CHANNEL FM VOICE PHASE-LOCK LOOP DEMODULATOR

The optimization of a phase-lock demodulator for single channel voice has been carried out by C. M. Thomas.* The basic concept involves using an approximation for the power spectrum of the speech signal which allows for an evaluation of an optimum loop bandwidth and threshold. The approximation used for the voice power density is given by:

$$\Phi_v(\omega) = \frac{\omega_o^4}{(-\omega^2 + j\sqrt{2}\,\omega_o\omega + \omega_o^2)(-\omega^2 - j\sqrt{2}\,\omega_o\omega + \omega_o^2)} \tag{A-1}$$

where

$\omega_o = 2\pi\ (800)$ rad/sec

This voice spectrum is typically amplified, filtered in a premodulation filter, and then applied to a modulator. When this voice power spectral density is applied to a demodulator whose phase transfer function is given by

$$H(\omega) = \frac{j\sqrt{2}\,\omega_n\omega + \omega_n^2}{-\omega^2 + j\sqrt{2}\,\omega_n\omega + \omega_n^2} \tag{A-2}$$

where

ω_n = the loop bandwidth of a standard second order loop.

One can then derive the mean square phase error in the loop from

$$\overline{\epsilon_v^2} = \int_{-\infty}^{\infty} \Phi_\theta(\omega)\,|1 - H(\omega)|^2\, d\omega \tag{A-3}$$

*C. M. Thomas, "Optimization of Phase-Lock Loop Demodulator for Single Channel Voice," Microwave Journal, Vol. 7, June 1967.

where

$\Phi_\theta(\omega)$ = the transmitted phase spectrum which is a modification of Equation (A-1) to include the effects of amplification, filtering, and the modulator.

The combination of this voice mean square phase error and the noise mean square phase error given by

$$\overline{\epsilon_n^2} = \frac{3.3\, f_n\, \Phi_n}{c} \tag{A-4}$$

where

$\frac{c}{\Phi_n}$ = the carrier-to-noise density ratio at the input to the demodulator

leads to the total mean square phase error for the loop

$$\overline{\epsilon_T^2} = \overline{\epsilon_v^2} + \overline{\epsilon_n^2} \tag{A-5}$$

It is this total mean square phase error in the loop which must be optimized with respect to the loop bandwidth. This optimum f_n is obtained from the solution of

$$\frac{\partial \overline{\epsilon_T^2}}{\partial f_n} = 0 \tag{A-6}$$

The solution to Equation (6) yields

$$f_{no} = \frac{4}{3.3}\, \overline{\epsilon_{v_2}^2}\, \frac{c}{\Phi_n} \tag{A-7}$$

where

f_{no} = the optimum bandwidth for the second order loop.

In Equation (A-7) the quantity $\overline{\epsilon_{v_2}^{\,2}}$ is given by

$$\overline{\epsilon_{v_2}^{\,2}} = \frac{1}{2\pi} \int_{-6.0\pi \cdot 10^3}^{6.0\pi \cdot 10^3} \frac{2\sqrt{2}\, \omega_o^{\,3}\, \overline{\Delta\omega^2}\, \omega^2\, d\omega}{\omega_n^{\,4}(\omega^4 + \omega_o^{\,4})} \tag{A-8}$$

The difference between Equation (A-8) and the work of Reference 1 lies only in the limits of Equation (A-8). In this case

$$\overline{\epsilon_{v_2}^{\,2}} = 0.876\, \frac{f_o^{\,2}\, \overline{\Delta f^2}}{f_n^{\,4}} \tag{A-9}$$

Equation (A-8) represents an approximation for the solution to Equation (A-8) and is valid only when $f_{no} > 3.0$ kHz.

The quantity $\overline{\epsilon_T^{\,2}}$ is related to the loop threshold in that the loop threshold is said to occur when the probability that $\overline{\epsilon_T^{\,2}}$ exceed $\pi/2$ radians for some P percentage of the time. Therefore, it can be seen that the loop threshold is related to $\overline{\epsilon_T^{\,2}}$ which, in turn, is related to the loop bandwidth. The solution to Equation (A-6) apportions the phase errors in the loop such that

$$4\, \overline{\epsilon_v^{\,2}} = \overline{\epsilon_n^{\,2}} \tag{A-10}$$

The final derivation required to complete the optimization consists of obtaining a relationship between P and $\overline{\epsilon_T^{\,2}}$. Thomas demonstrates that at threshold

$$\overline{\epsilon_T^{\,2}} = 5.5\ p \tag{A-11}$$

where

$$P = \frac{p}{100}$$

Using Equations (A-5), (A-10), and (A-11)

$$\overline{\epsilon_n^{\,2}} = \frac{4}{5}\,\overline{\epsilon_T^{\,2}}$$

$$\overline{\epsilon_n^{\,2}} = \frac{4}{5}\,(5.5p) \qquad \text{(A-12)}$$

Equations (A-4), (A-7), (A-9), and (A-12) lead to

$$f_{no} = \frac{4}{3.3}\,(0.876)\,\frac{f_o^{\,2}\,\overline{f^2}}{f_{no}^4}\,\frac{c}{\Phi_n}$$

$$f_{no}^5 = \frac{4}{3.3}\,(0.876)\left[f_o^2\, f_o^2\, \overline{\Delta f^2}\right]\frac{5 \cdot 3.3\, f_{no}}{4 \cdot 5.5\, p} \qquad \text{(A-13)}$$

$$f_{no}^4 = 0.796\left[\frac{f_o^{\,2}\,\overline{f^2}}{p}\right]$$

$$f_{no} = 0.944\left[\frac{\overline{\Delta f^2}\, f_o^{\,2}}{p}\right]$$

The loop noise bandwidth is given by

$$B_N = 6.67\, f_{no} \qquad \text{(A-14)}$$

Therefore,

$$B_N = 6.26\left[\frac{\overline{\Delta f^2}\,\overline{f_o^{\,2}}}{p}\right]^{1/4} \qquad \text{(A-15)}$$

The equation for threshold in the loop is now derived as

$$\frac{c}{\Phi_n B_n} = \frac{1}{2\,\overline{\epsilon_n^{\,2}}} = \frac{1}{2}\left[\frac{5}{(4)(5.5\,p)}\right] = \frac{0.11}{p} \qquad \text{(A-16)}$$

So for an in-lock confidence of 95 percent, threshold occurs at

$$\left(\frac{c}{\Phi_n B_n}\right) = \frac{0.11}{0.05} = 3.4 \text{ db}$$

in the loop. The output test tone-to-noise ratio at threshold is given by

$$\left(\frac{S}{N}\right)_o = \frac{3}{2} \frac{K^2 \overline{\Delta f^2}}{f_m^3} \left[B_N \frac{0.11}{p}\right] \qquad \text{(A-17)}$$

where

K = peak-to-rms factor for voice = 2.2 numeric = 6.8 db

$\overline{\Delta f^2}$ = mean square deviation of the voice signal

f_m = baseband truncation of the voice signal = 3.0 kHz

Equation (A-17) is the standard FM improvement equation in which the peak deviation of the test tone is made to correspond to $K\sqrt{\overline{\Delta f^2}}$ the peak deviation of the voice signal. Substitution of Equation (A-15) into (A-17) leads at threshold to

$$\left(\frac{S}{N}\right)_o = 0.33 \, K^2 \left[\frac{\overline{\Delta f^2}}{p}\right]^{5/4} \qquad \text{(A-18)}$$

above threshold the performance is found from

$$\left(\frac{S}{N}\right)_o = \frac{3}{2} \left(\frac{c}{\Phi}\right) K^2 \frac{\overline{\Delta f^2}}{f_m^3} \qquad \text{(A-19)}$$

where

$\left(\frac{S}{N}\right)_o$ = RMS output test tone-to-noise ratio achieved using a sine wave tone of frequency f_m and whose peak deviation is the same as that caused by the total power in the noise spectrum

$\sqrt{\overline{\Delta f^2}}$ = RMS deviation of the voice signal

f_m = Test tone frequency usually taken as 3.0 kHz or the uppermost frequency of the information spectrum.

K = Peak to RMS factor for voice spectrum

c/Φ = carrier to noise density ratio at the input to the demodulator

In Equation (18) $K\sqrt{\overline{\Delta f^2}}$ corresponds to the peak deviation caused by the voice spectrum or the test tone.

Equations (A-18) and (A-19) have been solved and the results are presented in Figure A-1. A second curve which is of interest has been derived from Figure A-1 and represents the threshold output test tone-to-noise ratio as a function of threshold carrier-to-noise ratio. The RF bandwidth required has also been calculated and the results are shown in Figure A-2. From Figure A-2 it can be seen that for

$$\frac{S}{N_o} = 24.0 \text{ db}$$

we find

$$\frac{c}{\Phi_T} = 47.0 \text{ db-Hz}$$

$$B_{RF} = 24.5 \text{ kHz}$$

The procedure used to derive Figures A-1 and A-2 is outlined below.

- For a given RF input predetection bandwidth the allowable RMS deviation of the voice signal was calculated using Carson's rule.

$$B_{RF} = 2f_m\left(1 + \frac{K\sqrt{\Delta f2}}{f_m}\right) \qquad \text{(A-20)}$$

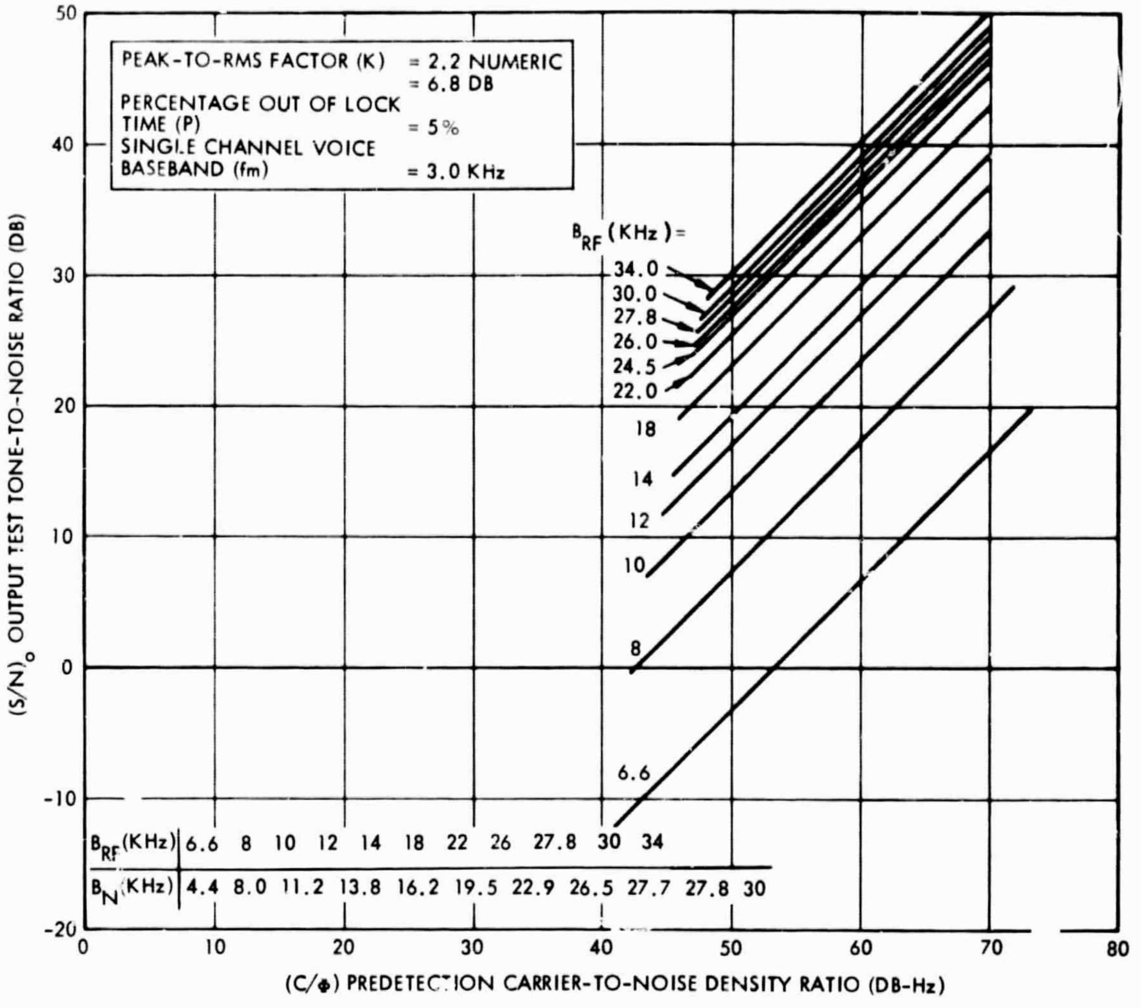


Figure A-1. Output Signal-to-Noise Ratio Versus Required c/Φ for single Channel Voice

- The $(S/N_o)_{OT}$ was then calculated using Equation (A-1) with

$$K^2 = 6.8 \text{ db}$$

$$p = 0.05$$

- Using this RMS deviation, Equation (A-19) was then solved for the performance above threshold as a function of (c/Φ).

Equation (A-2) can then be used to calculate the loop noise bandwidth (presented in tabular form in Figure A-1). It is important to realize that the threshold of the demodulator must be calculated as the carrier-to-noise ratio in the loop. The resulting carrier-to-noise density ratio obtained then determines the required predetection carrier-to-noise ratio in the RF bandwidth. The interrelationship between RF bandwidth and loop noise bandwidth is subtle. The RF bandwidth places a constraint upon the RMS deviation possible, whereas the loop noise bandwidth affects the threshold in the loop. The RMS deviation appears in the equation for both B_{RF} and B_N. The RF requirement is of interest for the design of the RF and possibly IF portions of the system, whereas the loop noise bandwidth affects the threshold in the loop.

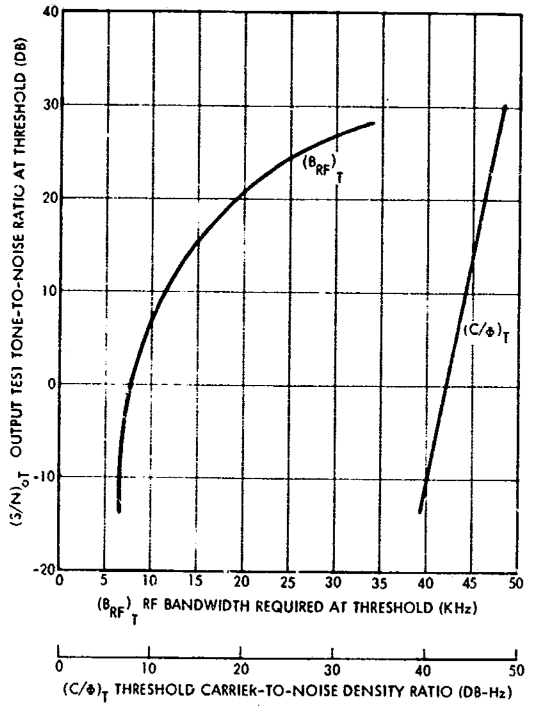


Figure A-2. Required Carrier-to-Noise Density Ratio (db-Hz) and RF Bandwith (kHz) at Threshold for an Optimized PLL Demodulator

APPENDIX B

THE ROLE OF CORRELATIONS IN NAVIGATION SATELLITE ERROR ANALYSIS

In navigation by satellite, the total navigation uncertainty is strongly affected by uncertainties in the determination of the ephemerides of the satellites. When two or more satellites are used, the ephemeris errors become highly correlated due to common error sources such as potential parameters, station locations, and measurement biases. A consequence of this correlation is a substantial reduction in the effect of the ephemeris errors on navigation error. The existence of this intersatellite correlation and its effect on navigation error is demonstrated by the results presented herein.

A particular navigation situation on the North Atlantic was assumed, with users at ten different locations and two stationary equatorial satellites providing coverage to the region. A tracking accuracy program was used to determine the uncertainty in satellite state vector estimation and in the estimation of associated parameters, and to evaluate the correlation between position errors for the two satellites. It was found that after a reasonable tracking interval (24 hours), the radial error correlation reached a high value (0.997). When this correlation was taken into account the effect of satellite ephemeris errors on navigation uncertainty was found to be reduced about 50 percent.

1. INTRODUCTION

For several years interest has been evidenced in the application of satellites to navigation of ships and aircraft. The principle of navigation by satellite is the same as that of traditional navigation by sun and stars. A navigator wishing to determine his location on the earth makes observations of bodies whose motions with respect to time (i.e., their ephemerides) are known. Traditional navigation makes use of angle measurements; navigation satellites, however, can be designed to utilize various measurement types. The present study is concerned with range measurements.

Two steps are involved in the operation of a navigation satellite system:

- The satellites are tracked, and their ephemerides determined and provided to the user (navigator)
- The user measures his range to the satellites and computes his position based on the satellite ephemerides provided.

The user's position computation requires at least three measurements; e.g., three range measurements, or two range measurements plus altitude. These can be measurements to the same satellite at different times (and hence different satellite locations) or to different satellites. The transit navigation satellite system uses the single-satellite technique, whereas the system analyzed here makes use of multiple satellites.

The configuration considered in this paper is illustrated in Figure B-1. Two synchronous equatorial satellites are located to provide coverage of the North Atlantic. The satellites are assumed to be tracked from stations located in New York and London. For such a system, the determination of the positions of the satellites will very likely be done in parallel. That is, the data obtained from all satellites will be used to estimate not only the satellite positions and velocities, but also the various nonsatellite parameters, such as station locations, measurement biases, and gravitational potential harmonics. For long tracking periods, these are principal contributors to the satellite position and velocity errors, and these errors are common to measurements to some or all of the satellites. The resulting satellite ephemeris errors can therefore be expected to be highly correlated. These correlations, in turn, cause significant reduction in the effect of the ephemeris errors on the user's position uncertainty.

These ideas were tested in a preliminary way in a previous study,* where it was shown that perfectly correlated satellite errors caused, for a range-differencing system (rather than the ranging system considered

---

*Study of a Navigation and Traffic Control Technique Employing Satellites, Vol. II - System Analysis, by D.A. Conrad, TRW Report No. 08710-6012-R000, December 1967.

here), a very significant reduction of the effect of satellite errors on navigation (compared to the case of uncorrelated ephemeris errors). Omitted, however, was an assessment of the magnitude of the correlations which might be expected in a realistic tracking situation. This paper presents results of further study to determine the actual correlations and the consequent effect of these correlations on navigation accuracy.

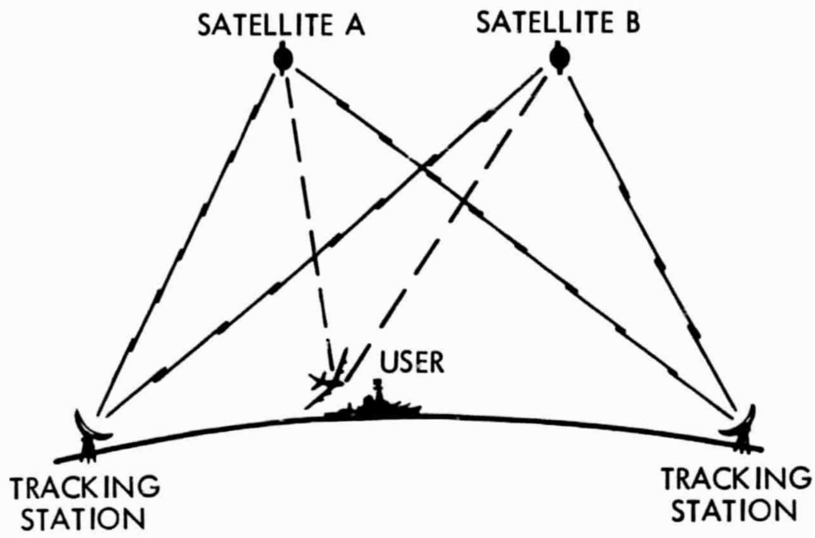


Figure B-1. Navigation by Satellite

The study consisted of runs on the TRW orbit determination program to determine tracking accuracy (including correlations) as a function of tracking time. The results indicate that as the tracking interval increases, the correlations between the satellite errors become more significant. The user navigation errors resulting from these correlated satellite errors are thereby reduced to values close to those obtained based on perfectly known satellite locations.

2. PROBLEM FORMULATION

Figure B-2 shows the subsatellite points and the grid of user locations considered. The tracking stations at New York and London are assumed to operate continuously, taking range measurements at a rate of 4 data points per minute. Values of the error sources are listed in Table B-1.

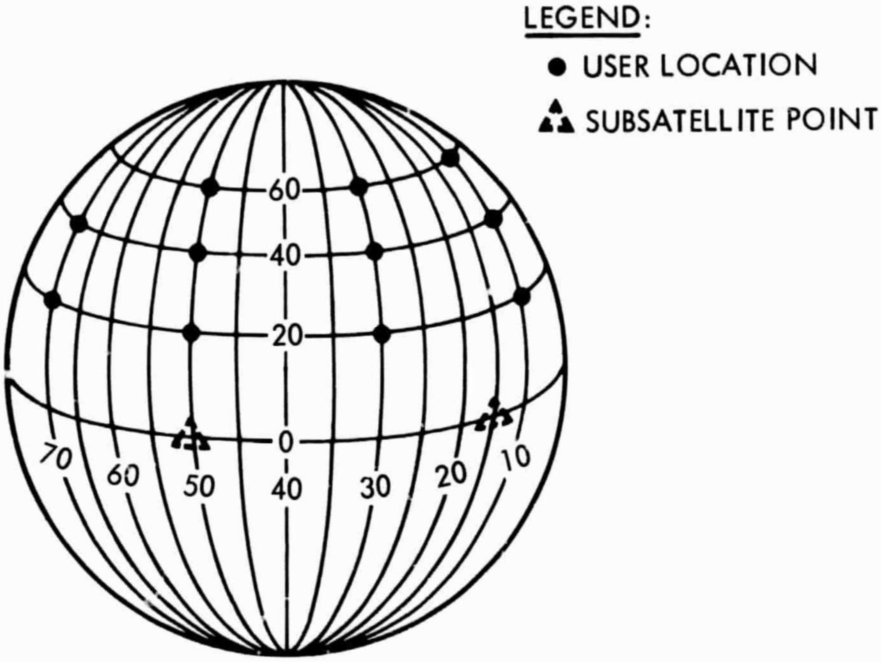


Figure B-2. User and Satellite Locations

Table B-1. Orbit Determination Error Sources

Measurement noise	30 ft	Gravitational potential uncertainties (1σ)**	
Measurement bias	70 ft*	μ	4.25×10^{-8}
		J_2	2×10^{-7}
Station location		C_{22}	4×10^{-8}
Longitude	100 ft	S_{22}	2×10^{-7}
Latitude	100 ft	C_{33}	6.1×10^{-8}
Altitude	100 ft	S_{33}	2.53×10^{-7}

*Assumed to be divided equally between satellite and ground station equipment.

**These values are nondimensional except for μ, which is in earth radii^3/minute^2.

It is assumed that the ephemeris determination includes estimates of the 28 quantities listed in Table B-2.

Table B-2. Parameters Estimated

Satellite A Position 3 components Velocity 3 components Bias 1 component	Satellite B Position 3 components Velocity 3 components Bias 1 component
New York Station Location 3 components Bias 1 component	London Station Location 3 components Bias 1 component
Gravitational potential parameters μ, J_2, C_{22}, S_{22}, C_{33}, S_{33}.	

The higher order potential terms are only weakly determined by the data, but the a priori uncertainty in these quantities serves to limit the overall satellite position accuracy attainable.

Current ephemeris data is transmitted to users through the satellites. The user computes his position with this data plus his range measurements to the satellites. In the case considered here, his position estimate is assumed to be calculated from single range measurements to each of two satellites at one point in time. One-sigma uncertainties contributing to the user's position determination errors are assumed to be as follows:

- Altitude: 300 feet
- Range measurement bias: 50 feet
- Measurement noise: 50 feet

The study was performed in two steps. First, the analysis of errors in the satellite ephemeris determination from tracking data was performed, and the intersatellite correlations were evaluated. Next, the accuracy with which a user could determine his position was evaluated for the cases of correlated and uncorrelated satellite errors.

3. ESTIMATION THEORY

The orbit estimation is by the well-known weighted-least-squares procedure, which is minimum variance when the measurements are weighted with the inverse variance of the measurement noise. In general, the procedure was to use a TRW computer program to generate a normal matrix of multiple satellite observations and to invert this matrix to yield a covariance matrix. Consider a linearized tracking model* associated with tracking the ith satellite:

$$y_i = A_i x_i + B_i z + \epsilon_i \tag{B-1}$$

where x_i is the satellite state vector consisting of positions, velocities, and possibly satellite oscillator bias. The z term is a vector of satellite independent parameters including station locations, biases, and gravitational potential parameters. y_i is the measurement vector; A_i and B_i are the appropriate partial derivative matrices; and ϵ_i is the measurement error.

For each satellite, the program generates a normal matrix of the form

$$Q_i = \begin{bmatrix} A_i^T W_i A_i & A_i^T W_i B_i \\ B_i^T W_i A_i & B_i^T W_i B_i \end{bmatrix} \tag{B-2}$$

where

$$W_i = \left[E\left(\epsilon_i \epsilon_i^T \right) \right]^{-1} \tag{B-3}$$

and then generates a giant normal matrix Q of the form

$$Q = \begin{bmatrix} A_1^T W_1 A_1 & 0 & 0 & \cdots & & A_1^T W_1 B_1 \\ 0 & A_2^T W_A A_2 & 0 & \cdots & & A_2^T W_2 B_2 \\ \vdots & & & & & \vdots \\ 0 & & & A_n^T W_n A_n & & A_n^T W_n B_n \\ B_1^T W_1 A_1 & B_2^T W_2 A_2 & \cdots & B_n^T W_n A_n & \sum_{i=1}^{n} & B_i^T W_i B_i \end{bmatrix} \quad (4) \tag{B-4}$$

---

*The reader is assumed to be familiar with the usual method of linearization about a nominal trajectory; x_i, y_i and z are deviations from nominal values.

The inverse of this matrix is the covariance matrix of the giant state vector:

$$x^T = \left(x_1^T \ldots x_n^T \; z^T \right)$$

The off diagonal terms $\left(A_i^T W_i B_i \right)$ of the normal matrix reflect an inversion into the desired correlations.

4. RESULTS

4.1 Orbit Determination

For the sample problem described above, the uncertainty in orbit determination is given in Table B-3. The figures in the first column of the table refer to tracking interval and propagation interval, respectively. That is, the notation 3/3 indicates that the station tracked the satellites for 3 hours, determined their emphermerides, and transmitted them to the satellite for relay to the users over the next 3-hour period. Using the propagated errors is equivalent to assuming that the user takes his fix 3 hours after the ephermerides are determined.

Table B-3. Satellit .'osition Estimation Error, Two Tracking Stations

Tracking/ Propagation Interval, (hr)	Radial Estimation Error (ft)		Radial Error Correlation Coefficient	In-Track Estimation Error (ft)		Cross Track Estimation Error (ft)	
	Independent Estimation	Joint Estimation		Independent Estimation	Joint Estimation	Independent Estimation	Joint Estimation
			SATELLITE A				
3/3	252	252	0.08	1169	1169	2097	2097
6/6	214	189	0.835	1133	982	1607	1358
12/12	79	71	0.818	353	317	141	129
2./12	68	62	0.997	88	87	51	44
36/12	65	60	0.997	57	50	41	33
			SATELLITE B				
3/3	249	249	0.08	1263	1263	1731	1731
6/6	231	207	0.835	1357	1183	1459	1267
12/12	79	73	0.818	336	306	137	123
24/12	69	62	0.997	88	88	37	33
36/12	67	60	0.997	51	44	30	25

The next columns in the table show the uncertainty in satellite position determination for two different data processing schemes: 1) independent estimation of each satellite state vector and the associated parameters;

2) joint estimation, as described in Section 3, where the tracking data from all (in this case both) satellites is used together to estimate both satellite state vectors and associated parameters.

The significant results shown in the table are the small radial errors (~60 feet) remaining after 24 or 36 hours of tracking (plus a 12-hour propagation period), and the high degree of correlation (0.997) in radial errors. For a navigation satellite system based on range measurements to satellites at synchronous altitude, the radial errors and their correlation properties are the principal contributors to user position determination accuracy. However, the navigation accuracies presented in the following section are based on the complete 12 x 12 satellite error covariance matrix, including <u>all</u> correlations. For the case of independent estimation, no correlation occurs, but the effect on the orbit estimation errors is minor.

Table B-4 presents the corresponding results when only one station (New York) tracks the satellites. It shows that the correlation coefficient remains lower and that the error magnitudes, especially in the in-track and cross-track directions, are larger. Because of the poor geometry (the satellite is essentially stationary), the state vector is very poorly determined after only 3 hours of tracking; the accuracy improves up to the 36 hour period considered in this study. Other TRW studies have shown that only minor improvement in accuracy is provided in tracking intervals longer than 36 hours.

Table B-4. Satellite Position Estimation Error, One Tracking Station

Tracking/ Propagation Interval, (hour)	Radial Estimation Error (feet)		Radial Error Correlation Coefficient	In-Track Estimation Error (feet)		Cross Track Estimation Error (feet)	
	Independent Estimation	Joint Estimation		Independent Estimation	Joint Estimation	Independent Estimation	Joint Estimation
			SATELLITE A				
3/3	∞	∞	0	∞	∞	∞	∞
6/6	1810	1800	0.06	6270	6200	13870	13840
12/12	371	364	-0.02	4188	3238	4307	4067
24/12	215	210	0.27	1211	785	1916	1794
36/12	152	140	0.47	763	697	1408	1324
			SATELLITE B				
3/3	∞	∞	0	∞	∞	∞	∞
6/6	12960	12960	0.06	35380	35370	92520	92510
12/12	195	190	-0.02	2620	2605	1832	1664
24/12	194	180	0.27	635	432	1587	1332
36/12	108	107	0.47	867*	768*	1069	993

*This reversal in the generally decreasing trend of errors can be attributed to cyclic effects during an orbit revolution and to the particular locations in the orbit where tracking and propagation occur.

4.2 Navigation Accuracy

The second step is to evaluate the effect of the satellite ephemeris error correlations on navigation accuracy. Users at the locations shown in Figure B-2 are assumed to estimate their positions and measurement biases. The navigator is assumed to make a minimum variance estimate of these quantities based on two simultaneous range measurements and a priori values of altitude, range bias, and the satellite positions. The corresponding four-dimensional position and bias error covariance matrix was computed, and the latitude and longitude errors were used to compute a C95, defined (analagously to CEP) as the radius of a circle, centered at the user's estimated position, which contains the actual position with a probability of 0.95. These C95's for the eleven users' positions were averaged to obtain a single value representative of the accuracy attainable with and without intersatellite correlations for the cases of one station tracking and two stations tracking. A similar calculation was made for the case of no satellite ephemeris errors (i.e., satellite positions are assumed perfectly known).

The results are shown in Table B-5 and are plotted in graph form in Figure B-3, which shows navigation accuracy (average C95) as a function of tracking interval. The absolute values of C95 would be lower for a user making repeated fixes (for example, updating his inertial navigation system at frequent intervals) or having three or more satellites available for range measurements. These results illustrate the improvement which results from satellite tracking error correlation. For an extended tracking interval (24 hours or greater), the effect of correlation is to remove about half the effect of the satellite ephemeris uncertainties.

Table B-5. Navigation Accuracy Results
(Average C95 - Feet)

Tracking/ Propagation Times	One Station		Two Stations		No Satellite Errors
	Uncorrelated	Correlated	Uncorrelated	Correlated	
6/6	16670	18020	971	1024	782
12/12	1640	1270	886	827	782
24/12	1020	915	858	809	782
36/12	1020	899	853	807	782

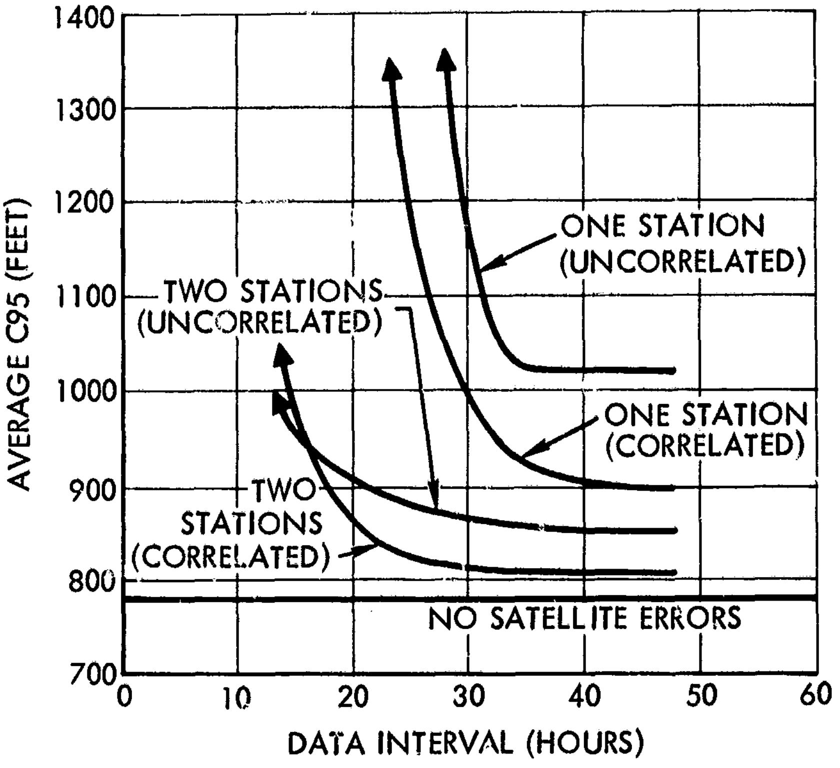


Figure B-3. Navigation Error as a Function of Orbit Determination Data Span

5. CONCLUSIONS

This presentation has considered one possible configuration of a navigation satellite system. The results illustrate the improvement in navigation accuracy that occurs due to the intersatellite correlation resulting from common sources in the orbit determination process. These correlations are shown to cause a reduction of the effect of satellite ephemeris uncertainties about 50 percent.

This system, although somewhat restricted geometrically, contains the essential elements of more complex systems employing 4 to 20 satellites in equatorial or inclined circular or elliptical orbits. For such systems, additional quantitative results are required, but the qualitative results obtained here can be expected to apply. Namely, the intersatellite correlations are of major significance in reducing the total effect of satellite ephemeris uncertainties on navigation errors. These correlations should be computed and their effects considered in the design of future systems for navigation by satellite.

APPENDIX C

RANGE-RANGE DIFFERENCE COMPARISON

This Appendix describes a simulation carried out to compare the relative accuracy of range versus range-difference position solution formulation in a hybrid inertial-NavSat system using a Kalman filter estimator. In the process, the difference between first fix and multiple-fix accuracies becomes apparent.

It is clear that in the case of a single-point-in-time solution, or equivalently where the inertial system is so poor or the time between solutions so long that the a priori position information is essentially useless relative to the measurements fix, that a set of N-range measurements with a common unknown bias, i.e., relative or pseudo ranges, are identical in information, content, and solution accuracy with the reduced set of N-1 range difference measurements. However, N-absolute range measurements would clearly be stronger than either of the above two cases. This is clear from an information viewpoint since the N-1 range differences can always be derived from the N-absolute ranges but not vice-versa.

However, with an inertial system capable of doing significant dead reckoning between fixes, and if the bias is also somewhat constant between fixes, then over a series of successive fixes that bias becomes better and better determined so that the N-relative range system may approach the N-absolute range solution. This set of inequalities may be illustrated in terms of relative strength or solution accuracy as follows:

Single Point in Time	Continuous Kalman Estimator With Inertial Hybrid
N-absolute ranges	N absolute ranges
better than ↓	better than ↓
N-relative ranges	N relative ranges
equal ↓	better than ↓
N-1 range differences	N-1 range differences

It is the purpose of this study to quantitatively estimate the extent of the inequalities in the above diagram. In order to reduce the problem to its essentials we consider the case of 4 satellites yielding 4 ranges or

3 range differences. Also, we consider only the line ed measurement equations and the case of a unit state transition matrix. Satellite ephemeris errors are ignored in this treatment (i.e., considered zero) in order to focus attention on the differing effect on user measurement errors.

The following definitions apply:

a) $\overline{X}_i$ = 3 vector of user position at time i (east, north or up at users location)

b) $\overline{g}_i$ = 3 vector of additive state noise on $\overline{X}_i$ since last fix (dead reckoning error)

c) $Q = \langle \overline{g}_i \overline{g}_i^T \rangle$ = dead reckoning state noise covariance

d) $\overline{Y}_i$ = 4 vector of range measurements to 4 satellites

e) $\overline{Z}_i$ = 3 vector of range difference measurements

f) M = 4 x 3 matrix of direction cosines of 4 lines of sight with respect to east, north, up at user

g) b_i = scalar range bias

h) r_i = range bias drift since last measurement

i) $R = \langle r_i^2 \rangle$ = range bias state noise variance

j) $\overline{\epsilon}_i$ = 4 vector of range measurement noise

k) $E = \langle \overline{\epsilon}_i \overline{\epsilon}_i^T \rangle$ = range measurement noise covariance

l) J_i = state estimate covariance matrix

We need not consider the single point in time case as it will fall out as a special case (first point) of the more general Kalman formulation.

<u>For Four Absolute Ranges</u>: The state vector is the 3 vector of x's, and we have

$$\underbrace{\overline{X}_{i+1}}_{3} = \underbrace{\overline{X}_i}_{3} + \underbrace{\overline{g}_i}_{3} \qquad \text{(C-1)}$$

Measurement Equation

$$\underbrace{\overline{Y}_i}_{4} = \underbrace{M}_{4x3} \overline{X}_i + \overline{}_i \qquad \text{(C-2)}$$

X

Then the Kalman state covariance propagation equation is

$$\underbrace{J_{i+1}}_{3x3} = \left[M^T E^{-1} M + (J_i + Q)^{-1}\right]^{-1} \tag{C-3}$$

For Four Relative Ranges: The common bias is carried in this case as an additional element of the state vector so that state vector is (4 x 1)

$$\begin{vmatrix} \overline{X}_i \\ \hline b_i \end{vmatrix} \tag{C-4}$$

Equation (1) still holds for X transition while for b:

$$b_{i+1} = b_i + r_i \tag{C-5}$$

The measurement equation is

$$\underbrace{Y_i}_{4} = M \overline{X}_i + \begin{vmatrix} 1 \\ 1 \\ 1 \\ 1 \end{vmatrix} b_i + \overline{\epsilon}_i \tag{C-6}$$

$$= \begin{vmatrix} M & \vdots & \begin{matrix} 1 \\ 1 \\ 1 \\ 1 \end{matrix} \end{vmatrix} \begin{vmatrix} \overline{X}_i \\ \hline b_i \end{vmatrix} + \overline{}_i \tag{C-7}$$

and the state covariance propagation equation is

$$\underbrace{J_{i+1}}_{4x4} = \left[\begin{vmatrix} M^T \\ \hline 1\ 1\ 1\ 1 \end{vmatrix} E^{-1} \begin{vmatrix} M & \vdots & \begin{matrix} 1 \\ 1 \\ 1 \\ 1 \end{matrix} \end{vmatrix} + \left(J_i + \begin{vmatrix} Q & \vdots & \\ \hline & \vdots & R \end{vmatrix} \right) \right]^{-1} \tag{C-8}$$

For Tnree Range Differences: The range differences may be considered as derived from the ranges by a linear differencing transform of the form (for example)

$$\underset{3\times 4}{T} = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 \end{bmatrix} \qquad \text{(C-9)}$$

Applying this to Equation (C-6), and noting that T annihilates the $\begin{vmatrix} 1 \\ 1 \\ 1 \\ 1 \end{vmatrix}$ vector we have for the measurement equation from (C-6)

$$\underset{3}{\overline{Z}_i} = T\,\overline{Y}_i$$

$$= TM\,\overline{X}_i + T\,\overline{\epsilon}_i \qquad \text{(C-10)}$$

The state covariance propagation equation is

$$\underset{3\times 3}{J_{i+1}} = \left[M^T T^T (TET^T)^{-1}\ TM + (J_i + Q)^{-1}\right]^{-1} \qquad \text{(C-11)}$$

Note however that since we will take E as a scalar σ^2 times the identity matrix (uncorrelated range errors) it can easily be confirmed that

$$W = T^T(TET^T)^{-1}\ T = \frac{\sigma^{-2}}{4} \begin{vmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{vmatrix} \qquad \text{(C-12)}$$

for any T matrix of suitable form. Consequently

$$\underset{3\times 3}{J_{i+1}} = \left[M^T WM + (J_i + Q)^{-1}\right]^{-1} \qquad \text{(C-13)}$$

Setting Q and R: In order to fix Q and R let us take the specification in the form of the variance Q_T and R_T respectively of a random walk in time T with steps at intervals Δ, the solution interval. This is equivalent to assuming white noise or a flat noise power density spectrum in velocity for both the dead reckoning (IMU) and the oscillator reference. The latter is equivalent to white frequency modulation noise. Then assuming linear growth with $n = T/\Delta$ we have as the state noise variance per step

$$q_1 = \frac{Q_T \Delta}{T}$$

$$r_1 = \frac{Q_T \Delta}{T}$$

and

$$\underbrace{Q}_{3x3} = q_1 I_3$$

$$R = r_1$$

Program Form: A program RRD was written to solve Equations (C-3), (C-8), and (C-13) directly by iteration with intermediate iteration results printed out at each iteration step as called for by the operator. The M matrix is formed in the program in terms of input data consisting of either azimuth and elevation angles of the satellites as seen by the user or spherical coordinates of user and satellites. Either of the three modes of solution (absolute range, relative range, or range difference) are available, corresponding to Equations (C-3), (C-8), or (C-11), respectively.

First Example—Symmetrical Satellites: For the first example we took an idealized case where the satellites were disposed one directly overhead and the other three at 30 degrees elevation angle and azimuths of 0, 120, and 240 degrees. Inertial DR error was taken as 1, 000 feet per hour and oscillator error as 10 feet per hour. Measurement error was taken as 50 feet. The results are shown in Figure C-1. It was confirmed that in this case for any given number of iterations all three solution modes were identical in recovery of horizontal components of position (east and north). In retrospect it is clear that this is a result of the satellite

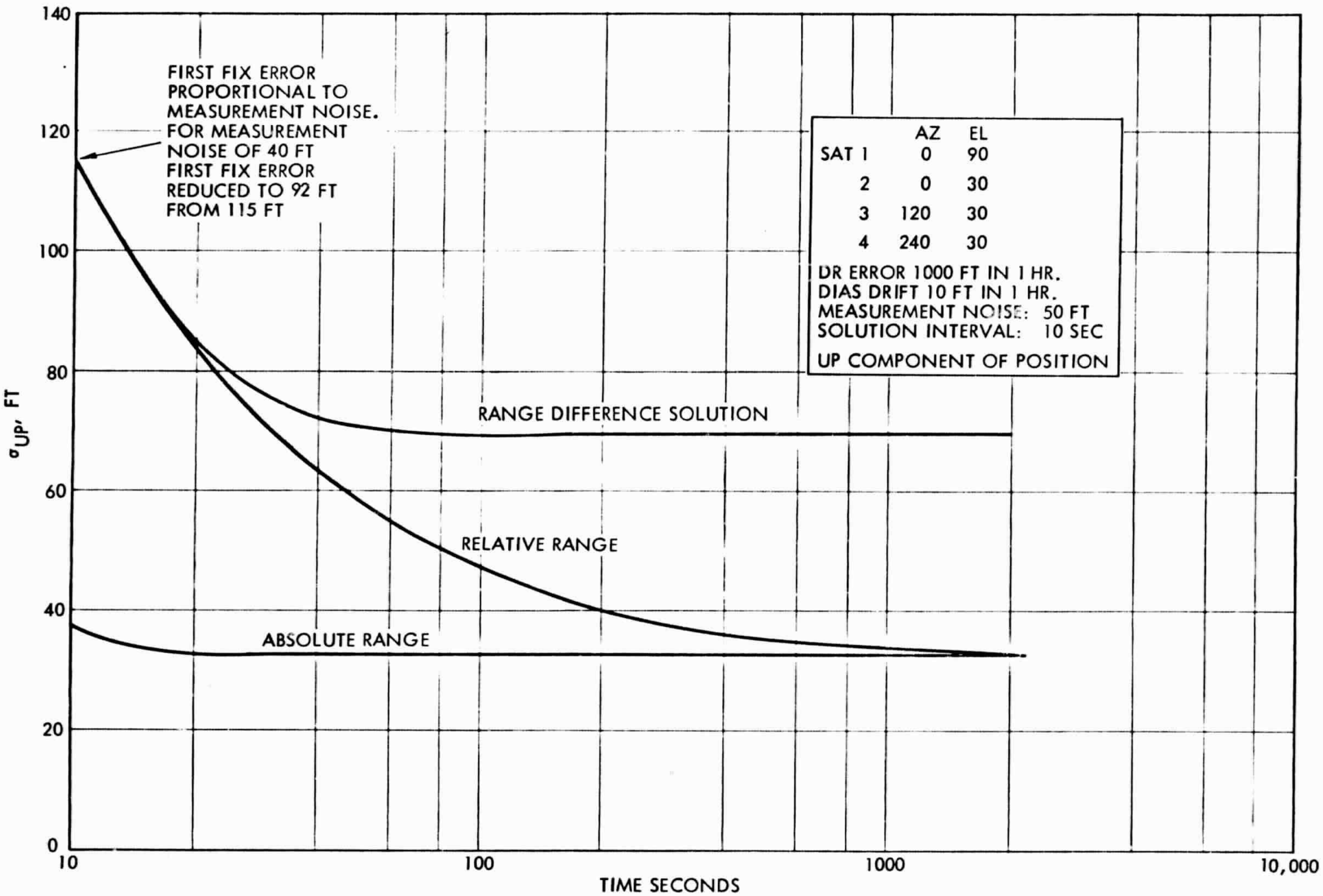


Figure C-1. Satellite Configuration—Symmetrical symmetry—a common error in all 4 ranges would not cause any error in the recovered horizontal components of position, only the vertical. The up component, however, differs significantly between the various solutions so as to confirm the inequality

$$\begin{pmatrix}\text{Range Difference}\\ \text{Error}\end{pmatrix} \geq \begin{pmatrix}\text{Relative Range}\\ \text{Error}\end{pmatrix} > \begin{pmatrix}\text{Absolute Range}\\ \text{Error}\end{pmatrix}$$

the equality holding only on the first iteration (like single-point-in-time). The second inequality asymptotically approaches equality for small oscillator bias drift after a large number of iterations.

Second Example—Best Satellite Configuration: All subsequent runs used an actual instant from the proposed four satellites 30 degrees inclined circular constellation, this being the time showing the best goodness factor on Itoga s runs. The subsatellite points at this time were specifically:

Satellite 1	73.8 deg. E	17.1 deg.
Satellite 2	86.2 deg. E	17.1 deg. S
Satellite 3	110 deg. E	0 deg.
Satellite 4	147.4 deg. E	28.4 deg. N

The user was at

User	110 deg. E	40 deg. N

Figures C-2 and C-3 show, respectively, the up and north components of position error for the corresponding case of 1,000 ft/hour DR error. Figure C-2 shows the effect of various bias drift error levels. Note here that the bias drift error is ineffective until it exceeds about 10 to 100 feet per hour and that for any smaller value the relative or pseudo-range solution becomes significantly better than range difference after about 100 seconds or 10 iterations.

Figures C-4 and C-5 correspond to Figure C-2 in showing the north component error for various bias error levels but for DR error levels of 6,000 ft/hour and 60,000 ft/hour, respectively. The only significant difference in these results with increasing DR error is the increased error of the range difference solution and of the relative range solutions with high oscillator drift error levels of 1,000 ft/hour or more. The absolute

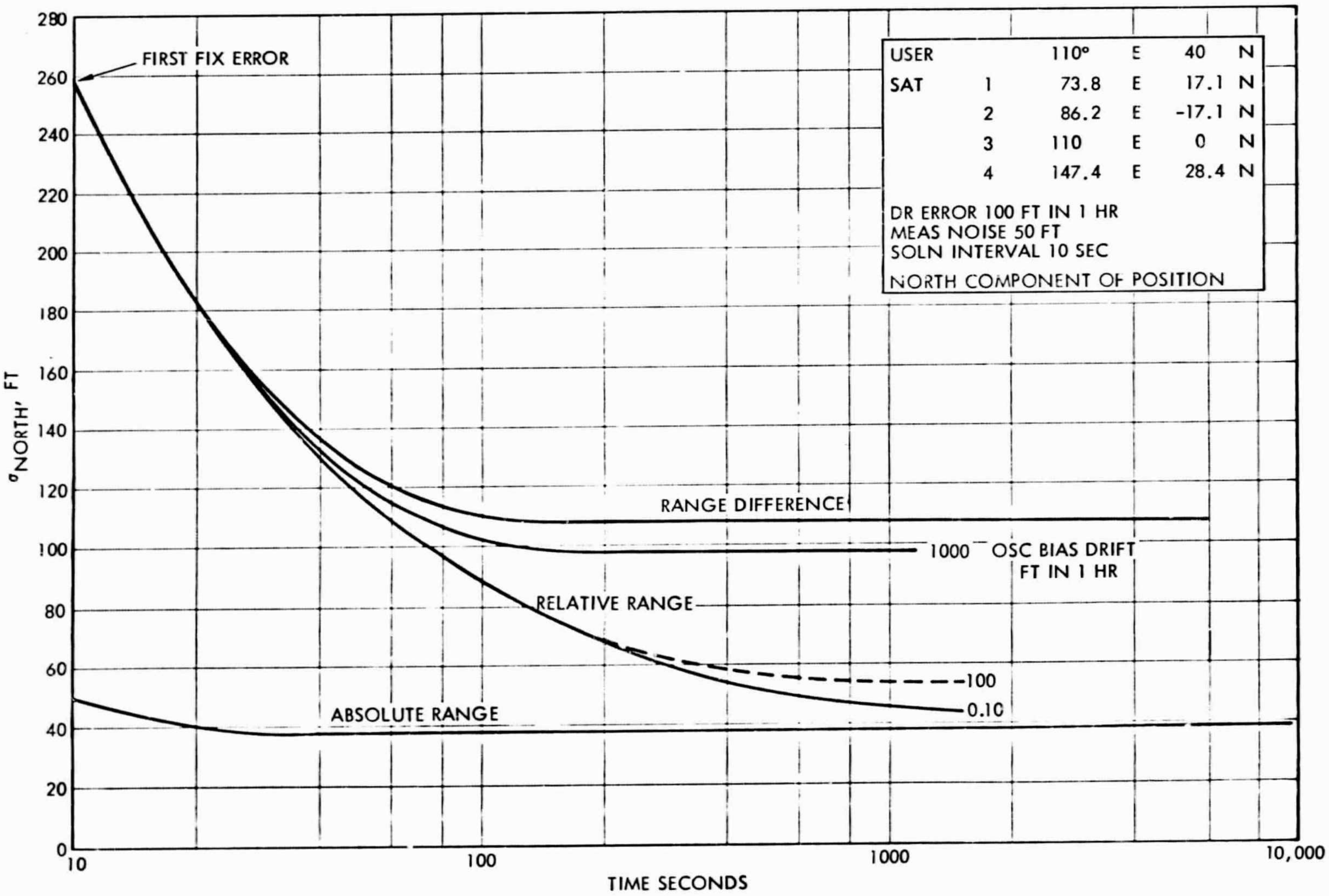


Figure C-2. Best Satellite Configuration

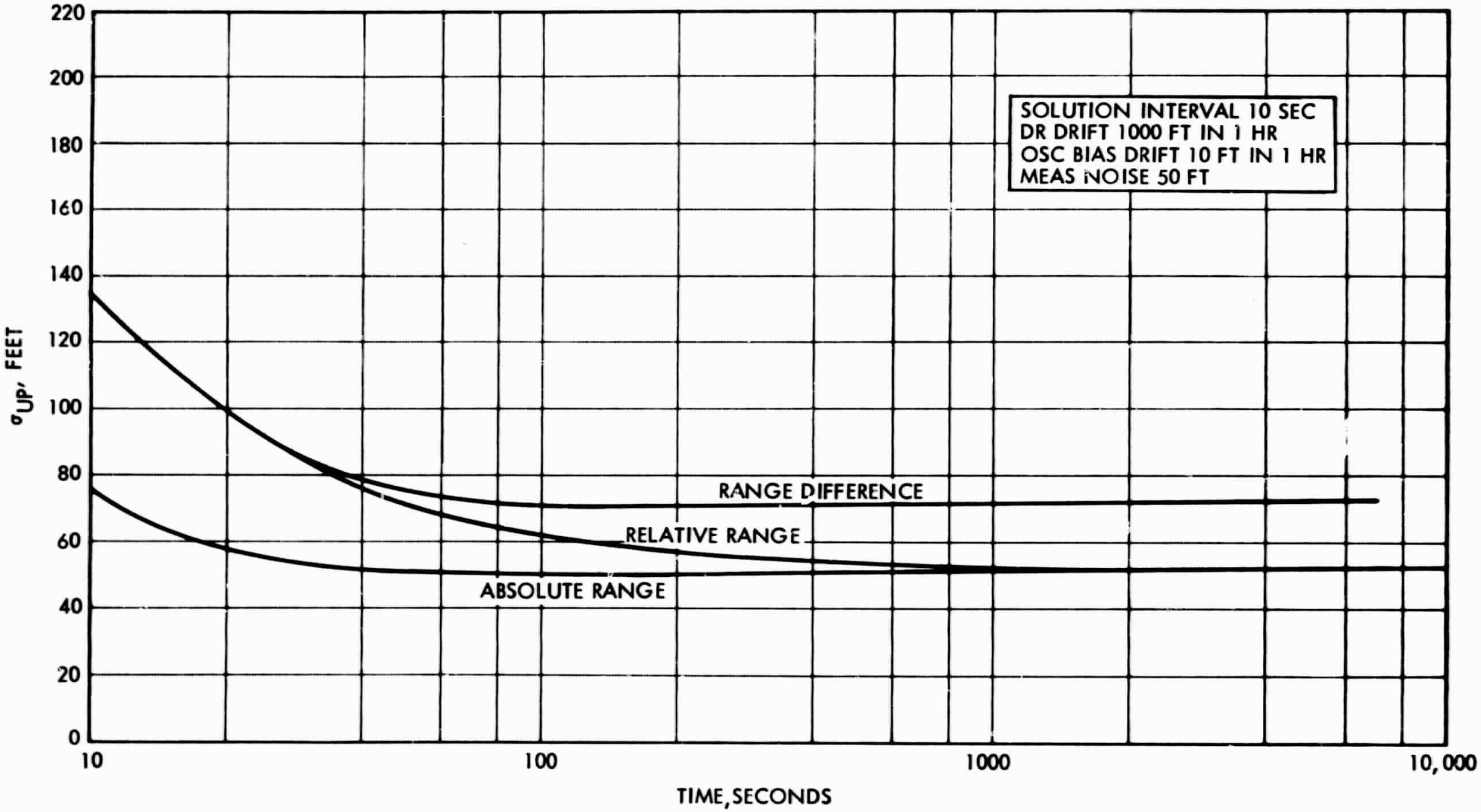


Figure C-3. Up Component of Position, Best Satellite Configuration

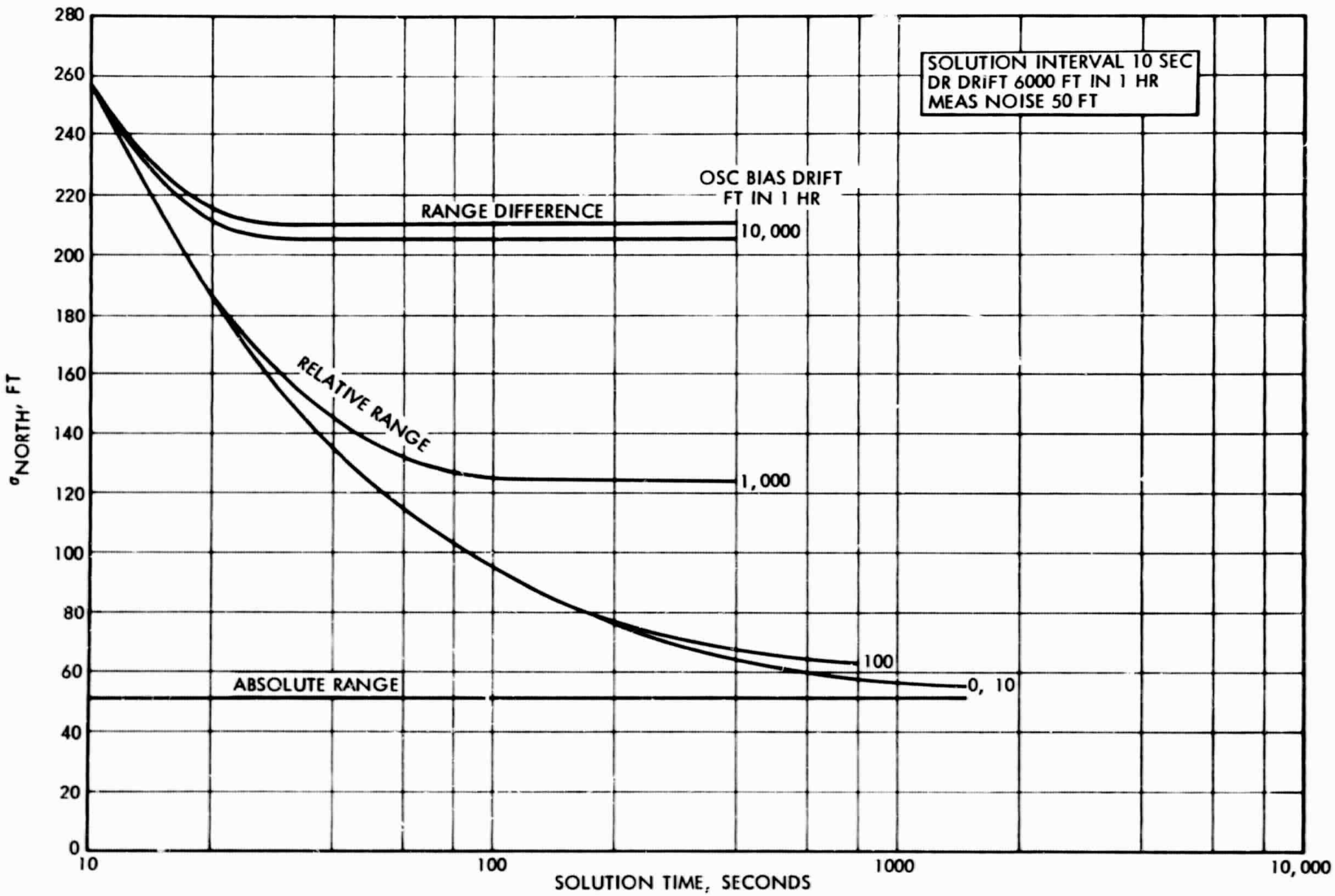


Figure C-4. North Component Recovery, Best Satellite Configuration

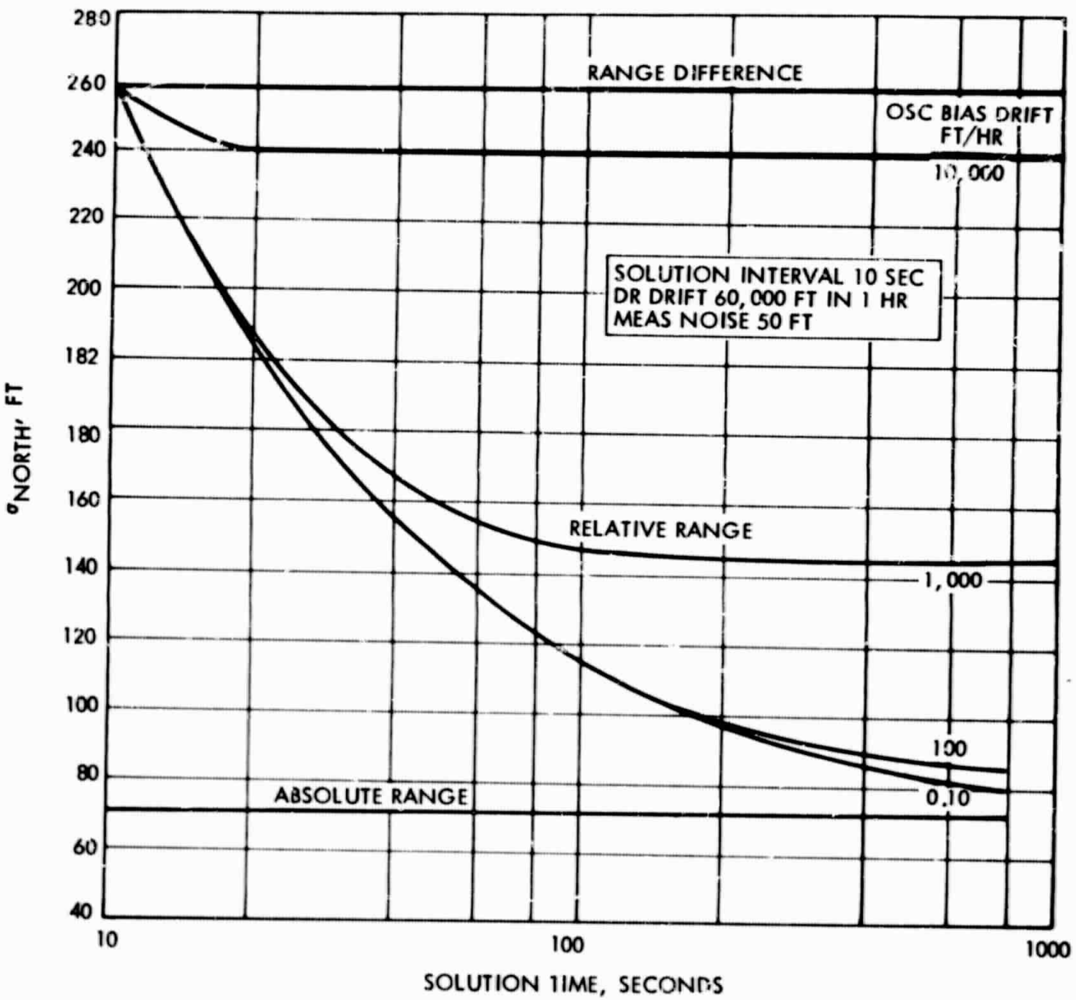


Figure C-5. North Component Recovery, Best Satellite Configuration range errors and asymptotic low oscillator drift rates are essentially controlled by the single-point fix accuracy in all cases and essentially independent of DR error (for DR error $\geq 1,000$ ft/hour).

A gratuitous result of the relative range solution is the calibration of the oscillator which is equivalent to the determination of time to a very high accuracy. Figure C-6 shows the range bias recovery in feet (or time in nanoseconds) for all the relative range cases previously considered. Figure C-7 summarizes the asymptotic bias recovery levels of Figure C-6 as a function of bias (osc) noise and DR noise levels. For a practical example, with 100 ft/hour oscillator bias noise (which is a pretty poor oscillator) and DR error no worse than 60, 000 ft/hour, time is recovered to about 35 feet or nanoseconds.

For oscillator and dead-reckoning (IMU) state noise of the anticipated magnitude the pseudo range-solution offers significant accuracy advantages over the range-difference solution, particularly in regard to north and up components. In addition, the pseudo-range solution provides an accurate absolute time calibration. The computer software mechanization is not significantly more complex and the receiver hardware is probably more straightforward.

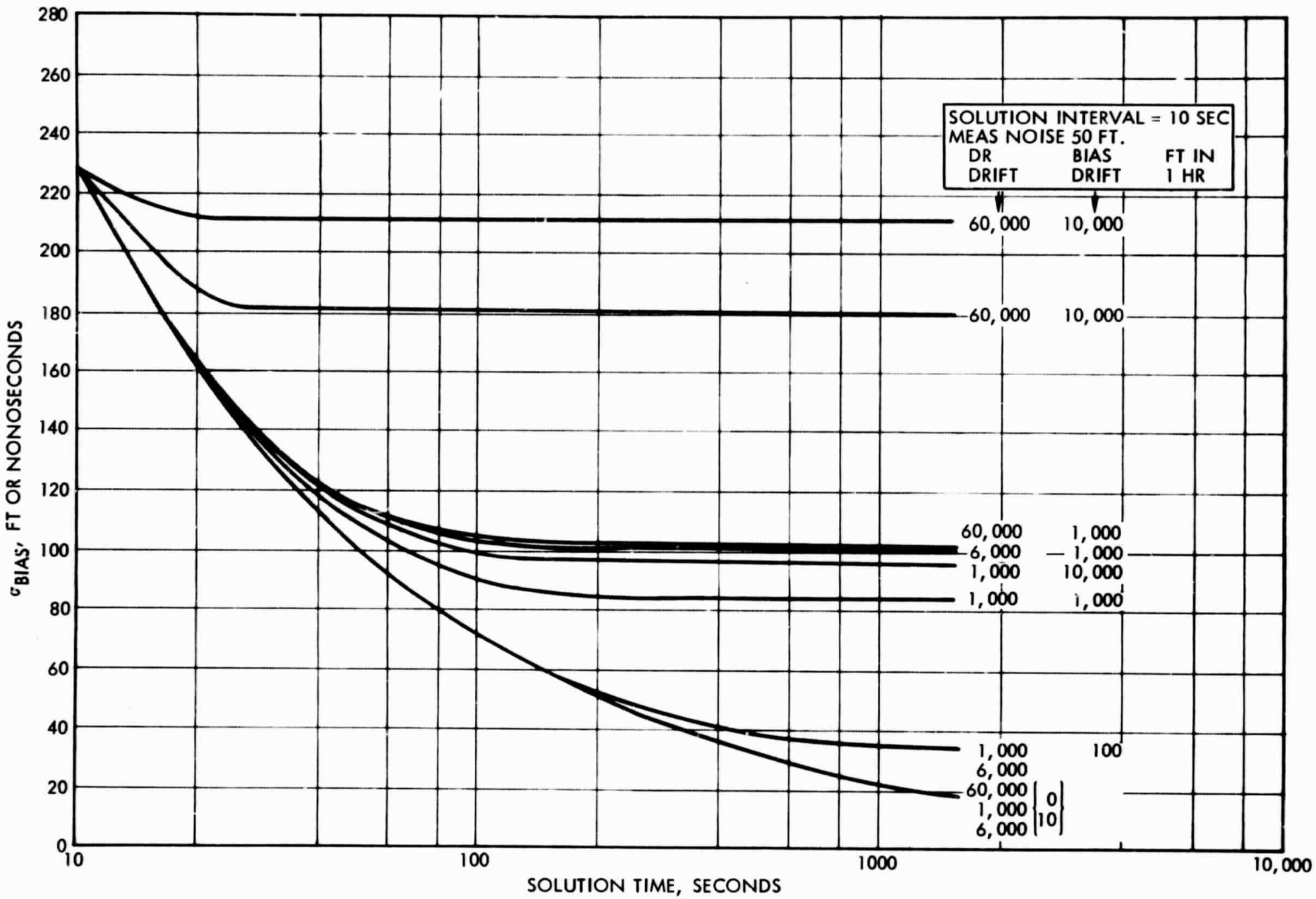


Figure C-6. Range Bias Recovery, Relative Range Solutions, Best Satellite Configuration

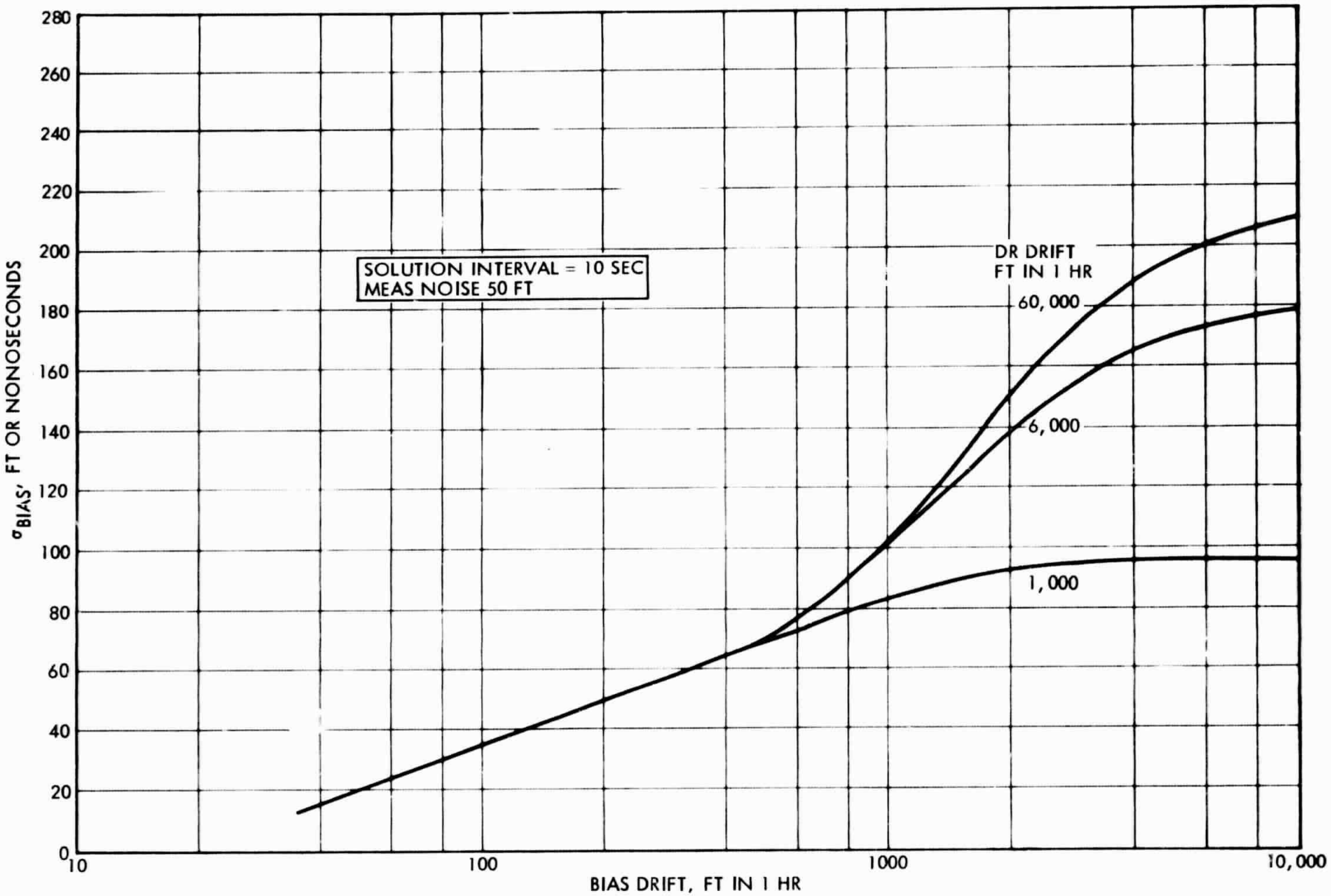


Figure C-7. Asymptotic Bias Recovery, Relative Range Solutions, Best Satellite Configuration

APPENDIX D

NAVIGATION/TRAFFIC CONTROL SATELLITE RELIABILITY ANALYSIS

1. INTRODUCTION

For a program of the size and duration of the Navigation/Traffic Control Satellite Program, it is essential to determine, in a rigorous manner, the quantity of spare satellites which must be provided to assume some level of confidence that sufficient satellites will be available to maintain coverage of the mission during its duration. For those phases where two dissimilar versions of the satellite will be used, it is important to allocate the chosen number of spares properly between the two versions so that the maximum utility can be gained. Finally, judicious decisions must be made as to whether increased confidence in mission coverage should be achieved by providing additional satellites or by upgrading the reliability of a lesser number of spares.

The analysis in this appendix is directed toward determining the Navigation/Traffic Control Satellite reliability and sparing requirements in accordance with the preceding paragraphs. Although this analysis does not represent a final optimization, the results have been used extensively in the recommended design and costing of the NTC Satellite.

2. DISCUSSION

The following discussion is directed toward evaluating the probability that, with 0, 1, 2, 3 . . . spare (or replenishment) satellites, each of several Navigation/Traffic Control System phases can be completed with, at most, zero, one or two satellites out of service. The definition of each operational phase is given in Table D-1. Several satellite configurations (designated A, B, and C) will be used for the various phases. No operating satellites launched for one phase can be used in another, and no B satellite can be used in place of a C satellite, nor a C in place of a B. (In special studies included at the end, only C satellites are used for Phase IIA, and Phase IA is considered to be July 1972 - July 1973.) Various levels of booster reliability are also considered.

Table D-1. Definition of Four Navigation/Traffic Control System Operational Phases

Phase	Duration	Elapsed Time	No. Satellites	Launch Time (months after start of phase)
I	7/72-6/74	23 months	2A's	0,2
II	6/74-1/76	19 months	1B * 2C	9 0, 15
IIA	6/74-1/80	67 months	1B * 2C	9 0, 15
III	1/76-1/80	48 months	2B 5C	3,6 0,10,17,24,36

* This analysis is also performed wherein phases II and IIA are comprised only of Configuration "C" satellites, which is the proposed program plan.

For each of the four operational phases, four sets of satellite/booster reliability, defined in Table D-2 are studied.

This analysis assumes that Configurations A, B, and C have the same reliability characteristics. Configuration C, as described in Volume III, has an MTTF of 45.5 months; but the weight margin available can readily be used for reliability improvement. In order to evaluate the system impact of a satellite reliability improvement program MTTF's of 60 and 75 months were also examined. The reliability versus time profiles are shown in Figure D-1. The exact nature of the satellite redesign to attain the higher levels was not investigated in the study. What is of interest in this analysis, however, is the savings in spare satellites when the reliability is so improved.

Since Configurations B and C satellites are not mutually replaceable, it is important to properly allocate the total number of spare satellites between B and C configurations. Obviously, in Phase III, an allocation of 5 spare satellites with, say 5 B's and 0 C's would be a very inefficient allocation indeed. In fact, there is always an optimum manner of distributing B and C spares to achieve maximum probability of not running out of spares in an operational phase. Figure D-2 demonstrates the effect of varying the distribution of B and C satellites (in Phase II, MTTF = 45.52 months) for several quantities of total spares. It is easy to see that the probability of having sufficient spares can indeed be maximized by the proper combination of B and C spares.

One is first inclined to think that the ratio of B and C spares should be allocated in direct proportion to the number of active B and C satellites required for the phase. However, since a considerable time gap is involved between the initiation of the phase with one satellite and the last launch (3 years in Phase III), the average periods of "B" and "C" coverage are different and the direct relationship does not apply. Unequal booster reliabilities for the two cases also account for a change in the allocation.

Table D-2. Booster/Satellite Reliability Configuration Studied for Each Operational Phase

	Booster Reliability For:		
Satellite MTTF	A-Satellites	B-Satellites	C-Satellites
45.52 months	.95	.95	.85
60 months	.95	.95	.85
60 months	.95	.97	.95
75 months	.95	.97	.95

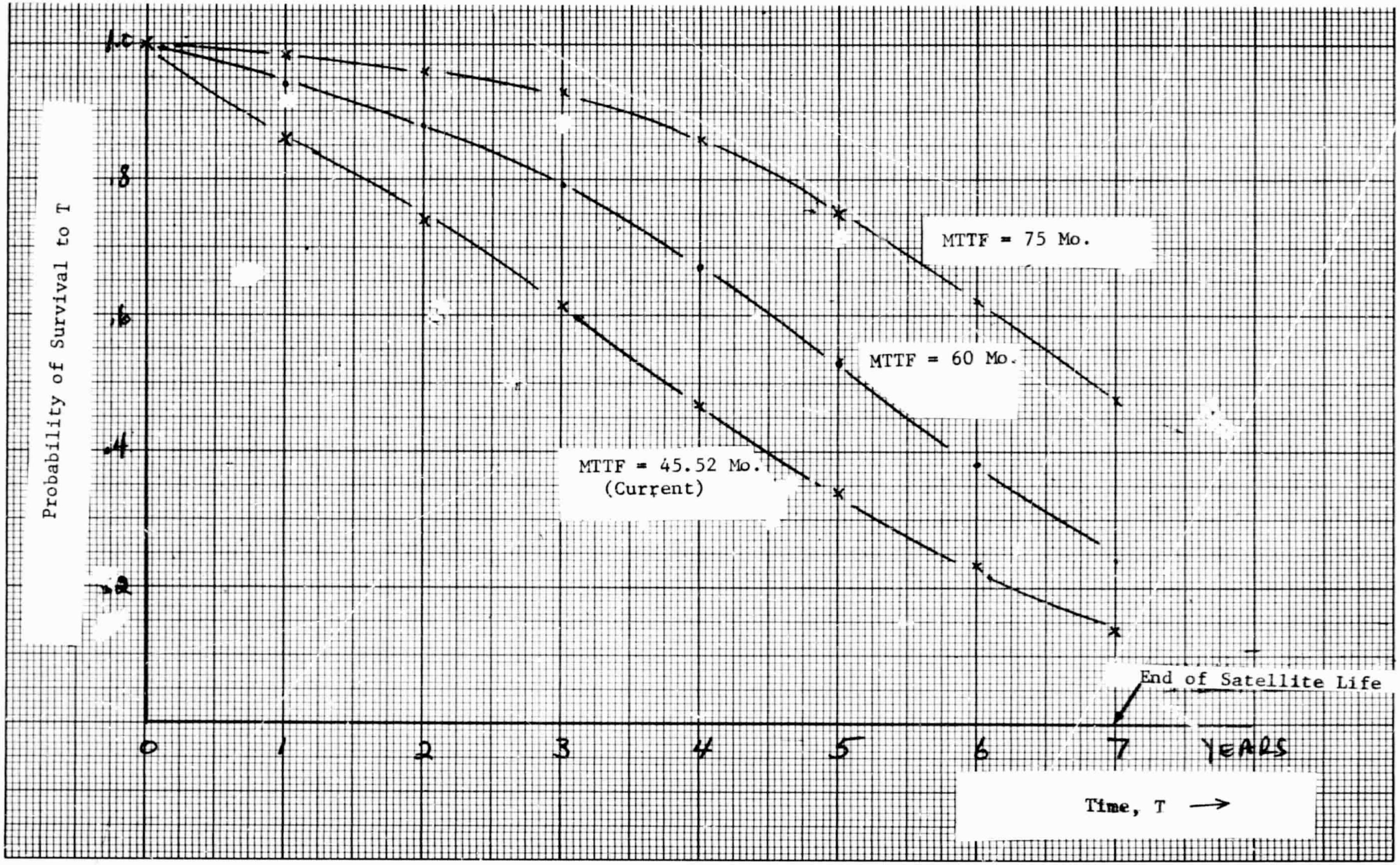


Figure D-1. Reliability vs. Time for Three Satellite Designs

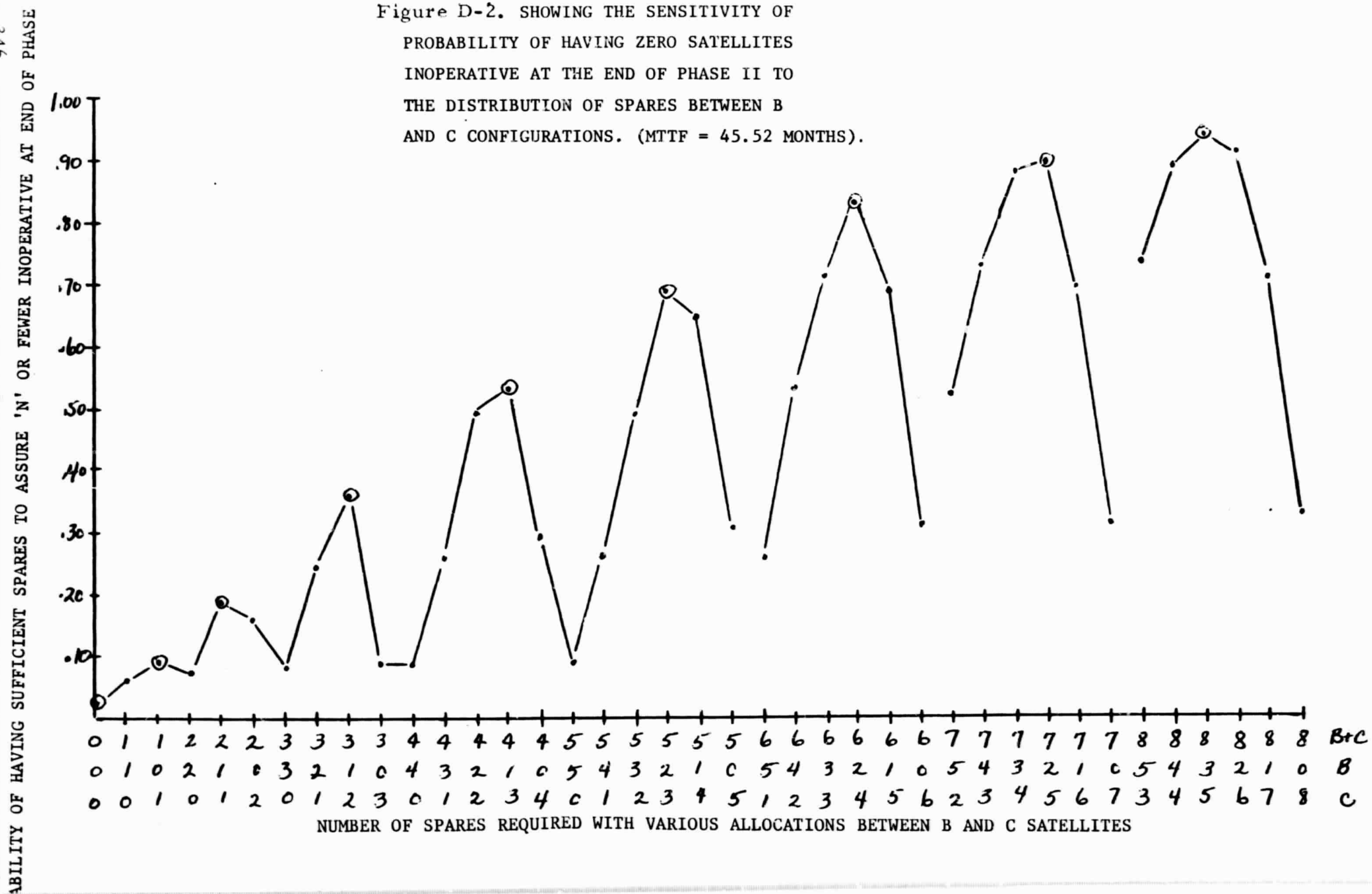


Figure D-2. SHOWING THE SENSITIVITY OF PROBABILITY OF HAVING ZERO SATELLITES INOPERATIVE AT THE END OF PHASE II TO THE DISTRIBUTION OF SPARES BETWEEN B AND C CONFIGURATIONS. (MTTF = 45.52 MONTHS).

3. MATHEMATICAL MODEL

A digital computer has been used to model the mission coverage characteristics of the Navigation/Traffic Control Satellite operational system with 0, 1, 2, 3 . . . spare satellites being made available. Specific parametric equations , relating spares, mission duration, launch schedule, orbital configuration and orbital maintenance are quite complex and different for each variation in one of these parameters. A more practical approach is to model the problem with the Monte Carlo technique.

Consider this problem formulation: n Satellites are to be launched at times $L_1, L_2, L_3, \ldots L_n$ into the mission. The n + 1 - th Satellite will be launched when any one of the first n satellites fails. If n_s spare satellites are available, what is the probability that n_s spares will be sufficient to completely replace all failed satellites and maintain n operational throughout the phase? Since the original satellites follow probabilistic behavioral laws, the launch time of the n + 1, n + 2 . . . satellite cannot be determined in advance and so the probability of it covering the remainder of the mission cannot be determined explicitly. But then consider that to find out how often those satellites will cover the mission we could, given enough satellites, conduct many hundreds of phase-length experiments in accordance with the formulated problem and record the number of experiments which yielded complete phase coverage and divide that number by the number of experiments made to determine the probability that the n_s spares gave full phase coverage.

The only reason to actually launch many hundreds of satellites is to assign some failure time to each of them. However, knowing the probabilistic behavior of the satellite, the Monte Carlo technique permits assignment of such failure times by means of the digital computer. If one were to visualize the problem of assigning a failure time to each of one thousand "number one" satellites, one thousand "number two" satellites and one thousand "number three" satellites, etc., in such a way as to reflect or simulate the outcome of one thousand hypothetical experiments, one would only need to be assured that he had chosen

$1000 \times (n + n_s)$ failure times with the same probability density function as that of the true failure time of the satellites, and that he had assigned each spacecraft's failure time in a completely unbiased (i.e., random) manner.

Consider now that a satellite's reliability function can be expressed as a Weibull curve

$$R(t) = e^{-t\beta/\alpha}$$

can be rewritten

$$t = (-\alpha \ \ln R)^{(1/\beta)}$$

Electronic computers have random number functions which select, in a random fashion numbers of value $0 < N < .9999 \ldots$ If a sufficiently large series of such values of N is used for R in the above expression, the resulting series of t's,

$$t = (-\alpha \ \ln N)^{(1/\beta)}$$

will be distributed in a manner identical to the failure times of a satellite with the given Weibull curve and in addition, if the series of failure times were assigned methodically to each satellite in succession, they would be assigned in an unbiased manner since N was random. It is then possible to look at the results of each set of hypothetical launches and spacecraft failures and tally the results, and, after sufficient trials, to integrate all experiments into an average performance of the strategy, which was the objective of the Monte Carlo analysis. This, then, is the methodology used by the computer in this analysis; the programs search out all possible combinations of allocations between B and C spares to find the one giving the highest probability of coverage.

The traditional exponential mathematical model is applied to describe the reliability behavior of most unit-level equipment on the satellite. However, the level of redundancy incorporated with most of the hardware causes the overall satellites' reliability model to be quite non-exponential.

Although the Navigation/Air Traffic Satellite reliability time profile is described by standard combinations of exponential expressions which account for the unit level redundancy, these expressions are quite cumbersome and, for the purposes of applying computer techniques to this study, it is desirable to find a simpler representation of the satellite model than the conventional one. The Weibull function of the form

$$R(t) = e^{-t^{\beta/\alpha}}$$

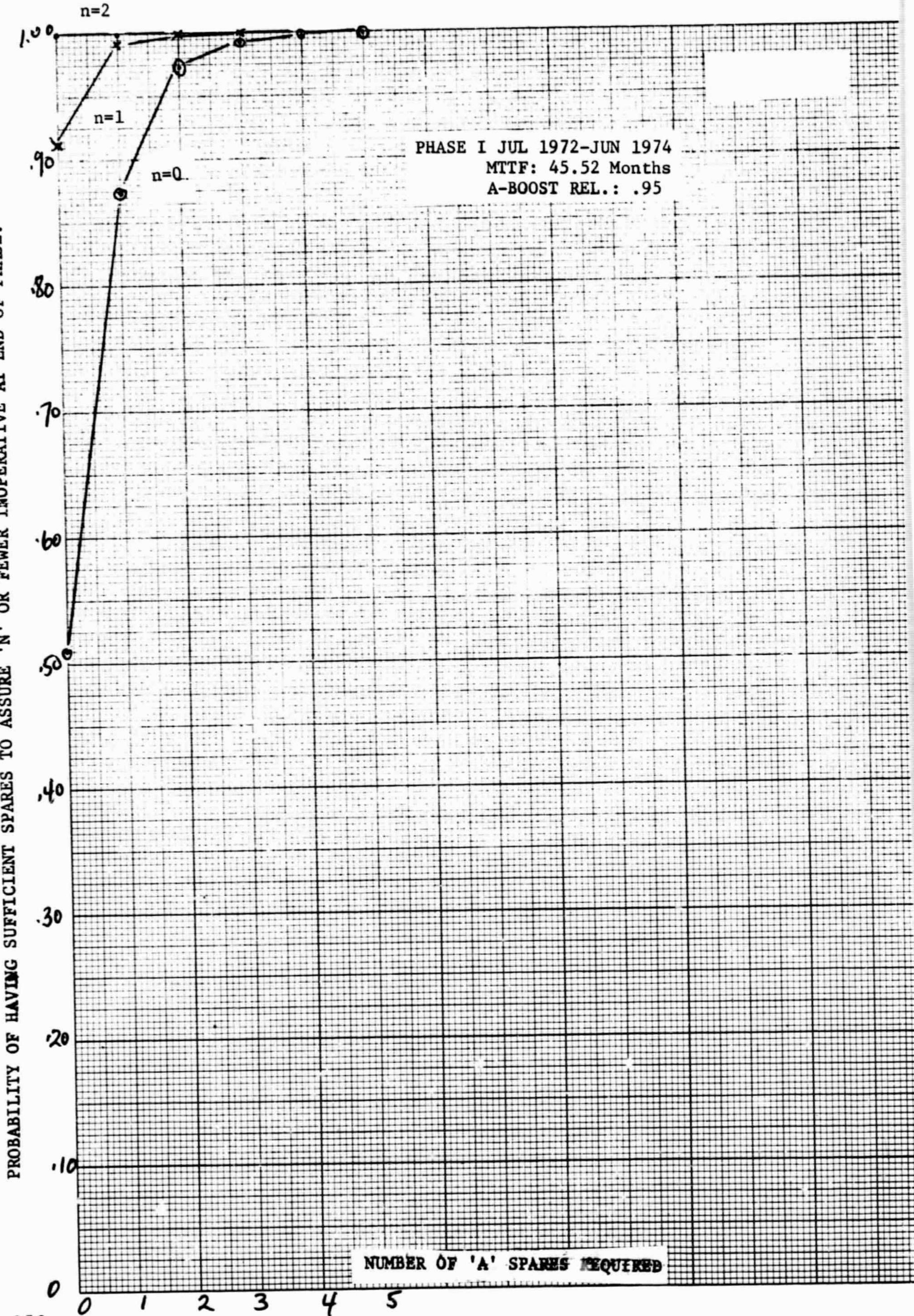
is used as that model. It is chosen for its obvious concise and highly useful format, and because its parameters α, β can be chosen in such a manner that the expression very closely matches the true reliability of the satellite. A Newton-Raphson Gradient technique is used to derive the α, β which best fits the Weibull function to the satellite R-T profile.

4. ANALYSIS OF RESULTS

Figures D-3 through D-18 depict the probability that any number of spare satellites will be sufficient to fully cover each mission phase, provided that the optimum allocation, shown in each case, is used. (Of course, during Phase I, where only Configuration A satellites are used, there is no problem with allocations. All spares are of the 'A' configuration.) In addition to showing the probability of not running out of spare satellites (i.e., having zero satellites inoperative) during a phase, Figures D-3 through D-18 also show the probability of having one (or fewer) and two (or fewer) satellites inoperative.

Although the optimum distribution of spare satellites is given in Figures D-3 through D-18, it is also interesting to know the effects of distributing the spares in a nonoptimum manner. Economic or operational considerations may warrant consideration of such nonoptimum strategies. To this end, Tables D-5 through D-8 are presented at the end of this study. These tables show the significant distributions which yield any sum of spare satellites, and the resulting probability of having zero, one, or two (or less) satellites operational at the end of each phase (P(0), P(1), and P(2), respectively). A graph similar to Figure D-2 could be constructed for each phase and each satellite/booster reliability combination.

Figure D-3.



n=2
n=1
n=0
PHASE I JUL 1972-JUN 1974
MTTF: 45.52 Months
A-BOOST REL.: .95
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF 'A' SPARES REQUIRED
0
1
2
3
4
5

Figure D-4.

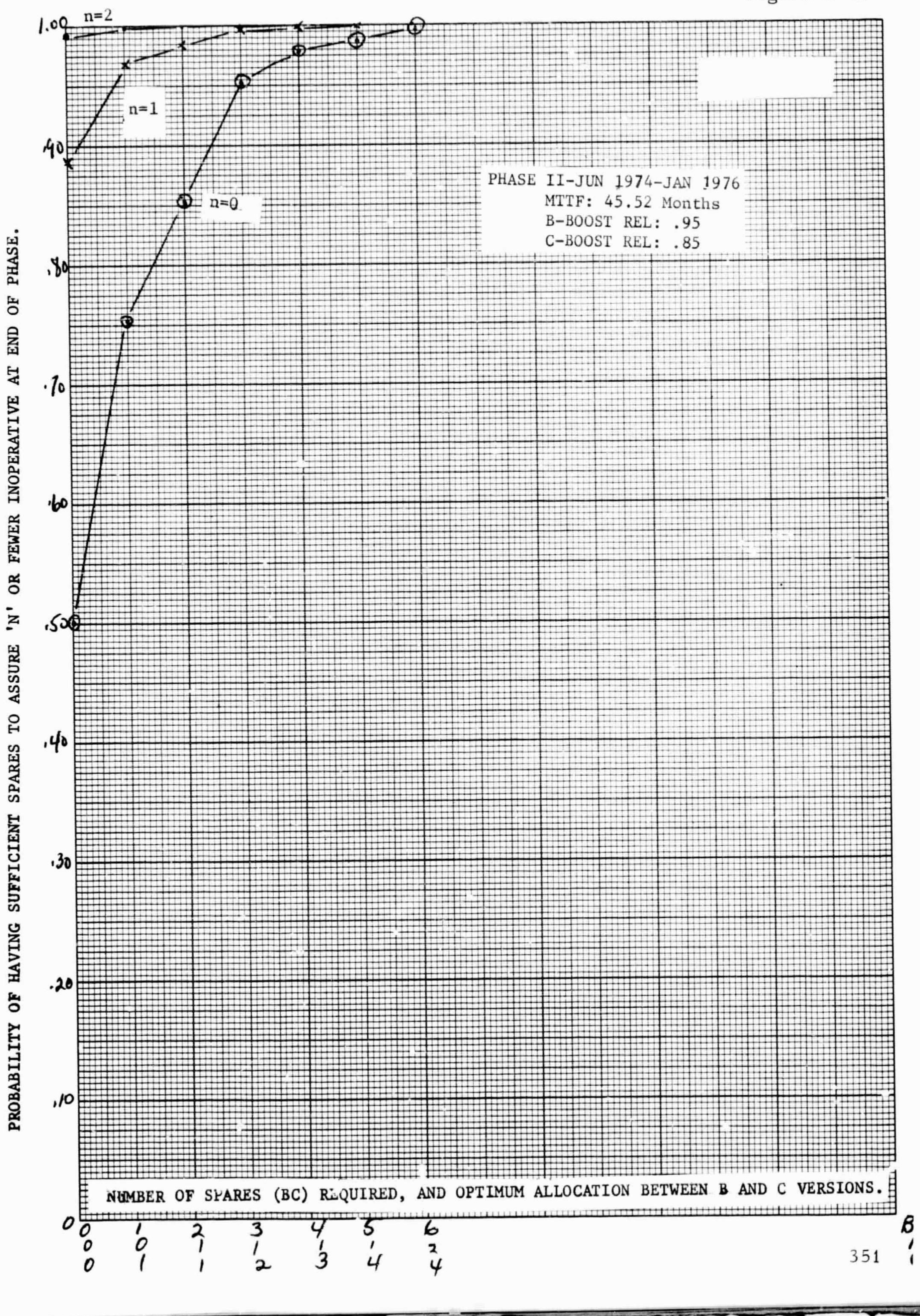
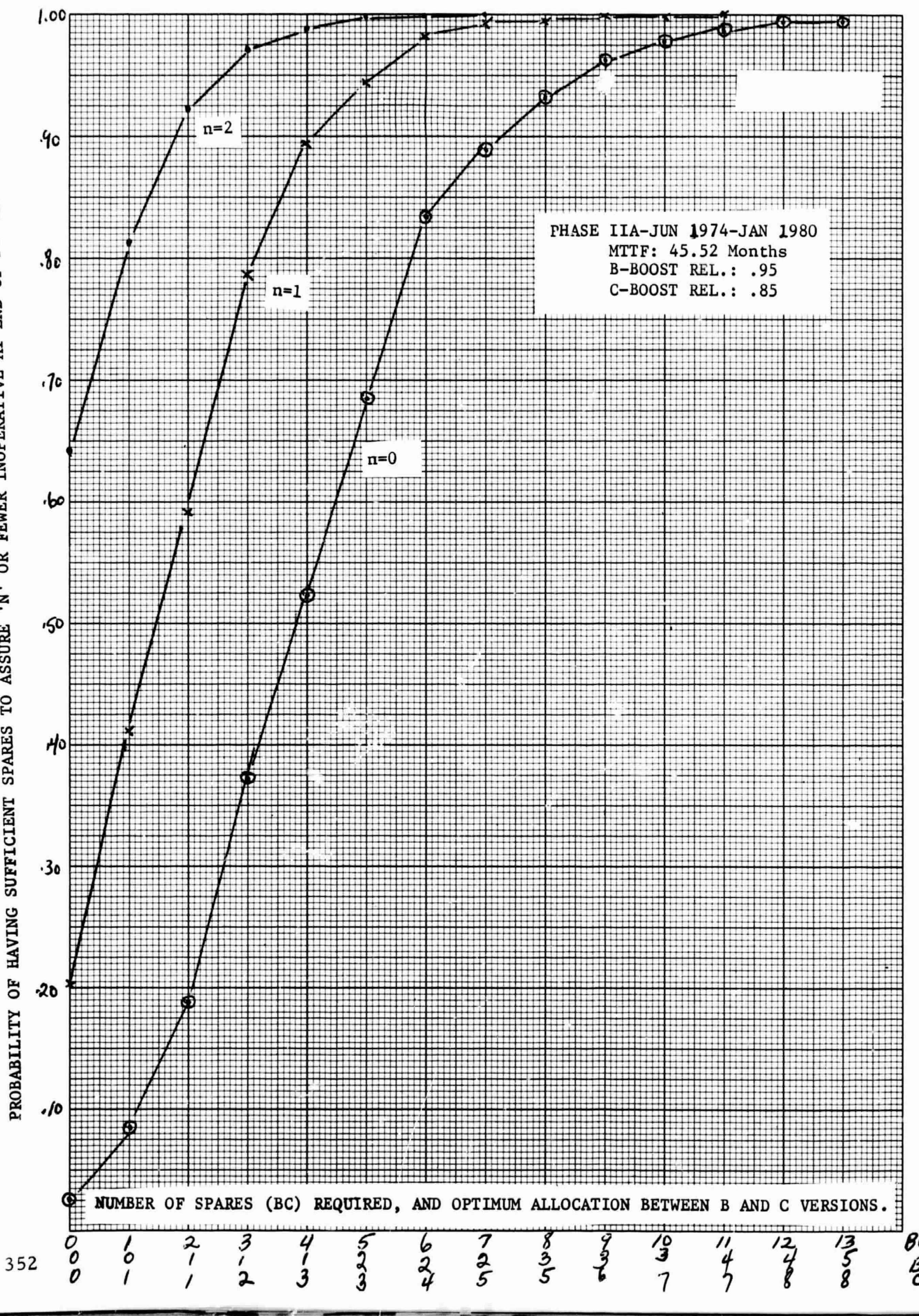

PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
n=2
n=1
n=0
PHASE II-JUN 1974-JAN 1976
MTTF: 45.52 Months
B-BOOST REL: .95
C-BOOST REL: .85
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
0 1 2 3 4 5 6
0 0 1 1 1 1 2
0 1 1 2 3 4 4
B
1
1

Figure D-5.



PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
PHASE IIA-JUN 1974-JAN 1980
MTTF: 45.52 Months
B-BOOST REL.: .95
C-BOOST REL.: .85
n=2
n=1
n=0
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
BC 0 1 2 3 4 5 6 7 8 9 10 11 12 13
B 0 0 1 1 1 2 2 2 3 3 3 4 4 5
C 0 1 1 2 3 3 4 5 5 6 7 7 8 8

Figure D-6

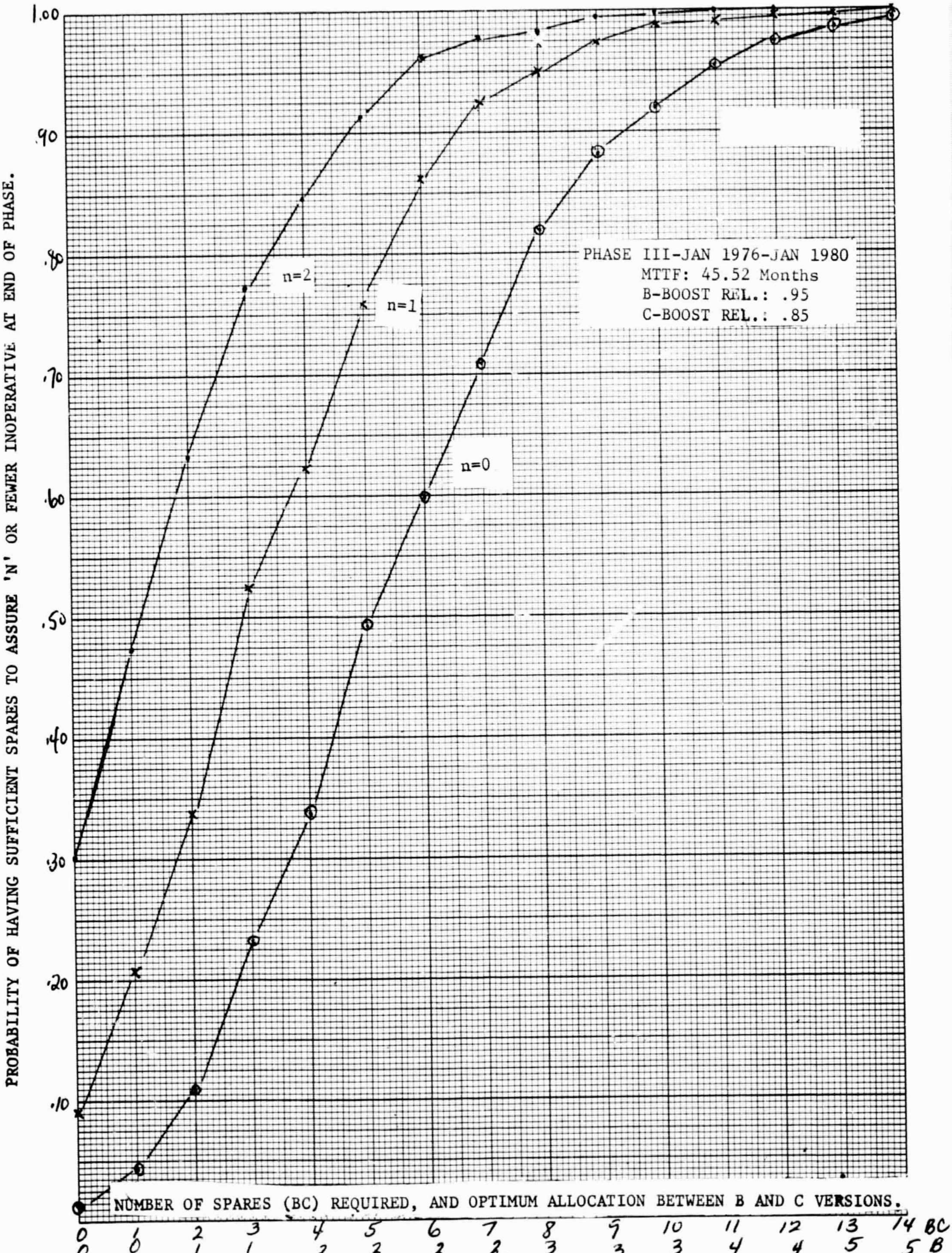

PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
PHASE III-JAN 1976-JAN 1980
MTTF: 45.52 Months
B-BOOST REL.: .95
C-BOOST REL.: .85
n=2
n=1
n=0
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 BC
0 0 1 1 2 2 2 2 3 3 3 4 4 5 5 B
0 1 1 2 2 3 4 5 5 6 7 7 8 8 9 C

Figure D-7.

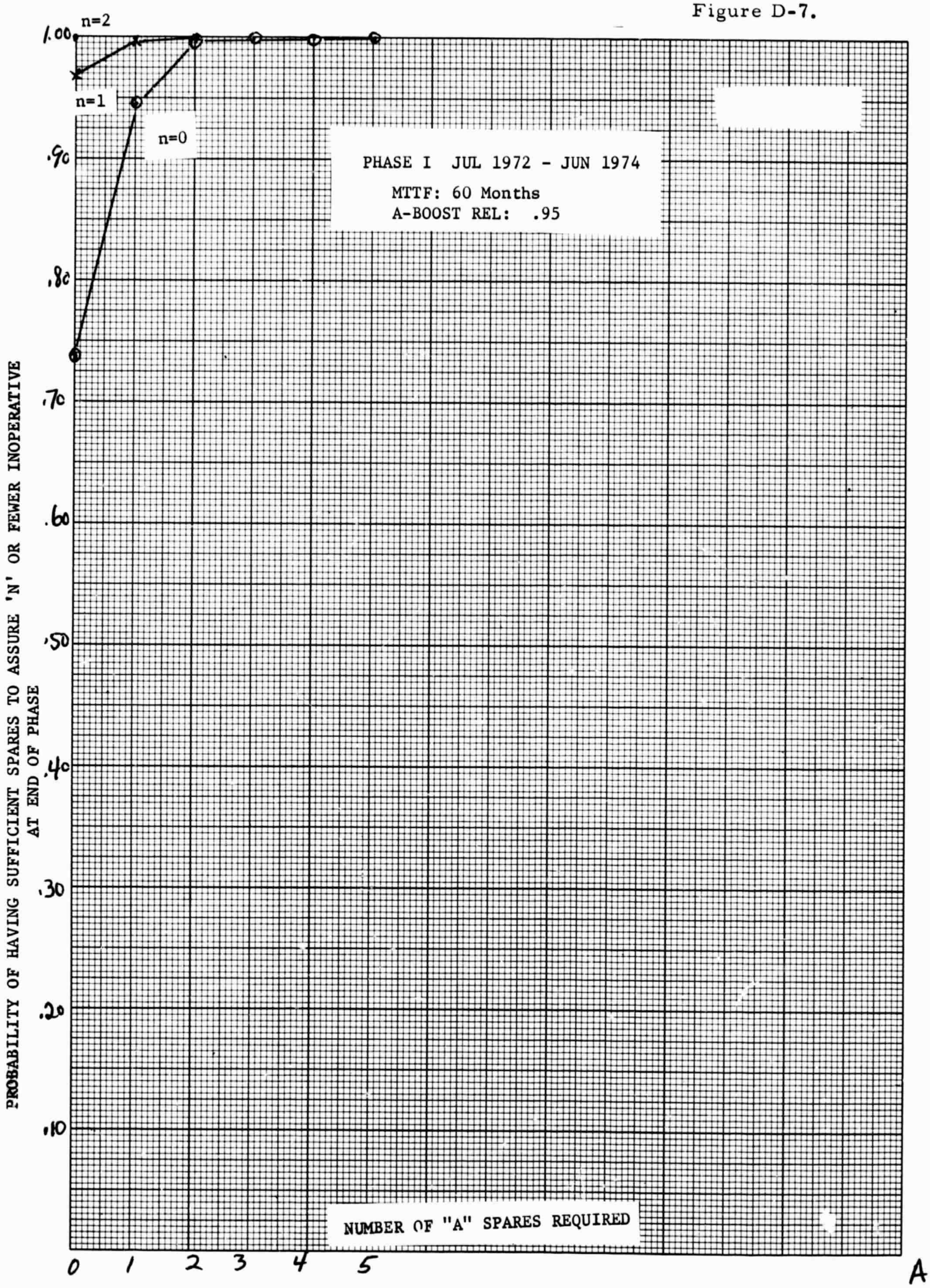

n=2
n=1
n=0
PHASE I JUL 1972 - JUN 1974
MTTF: 60 Months
A-BOOST REL: .95
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
NUMBER OF "A" SPARES REQUIRED
0
1
2
3
4
5
A

Figure D-8.

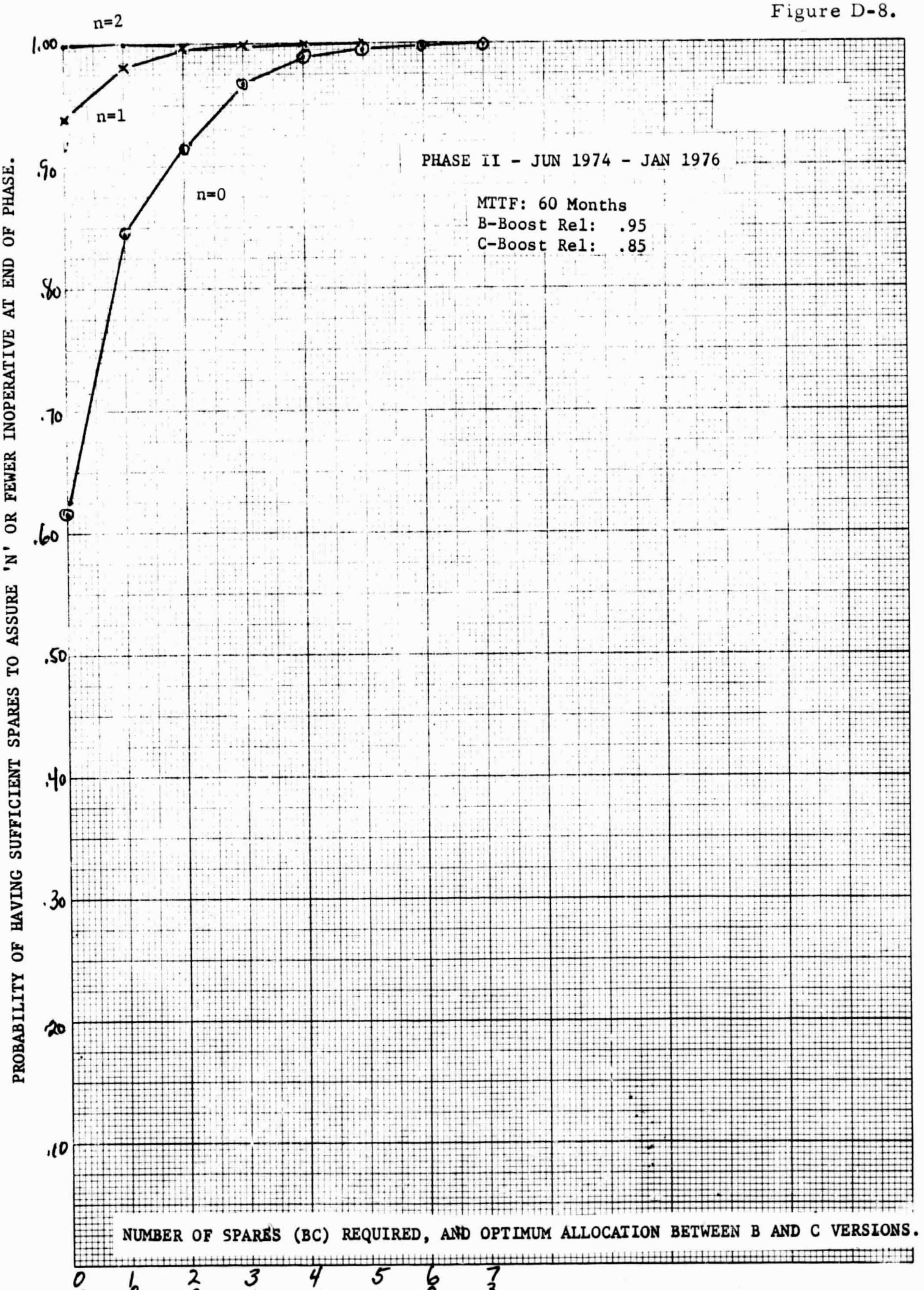

n=2
n=1
n=0
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
PHASE II - JUN 1974 - JAN 1976
MTTF: 60 Months
B-Boost Rel: .95
C-Boost Rel: .85
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
0 1 2 3 4 5 6 7
0 0 0 1 1 1 2 3
0 1 2 2 3 4 4 4

Figure D-9.

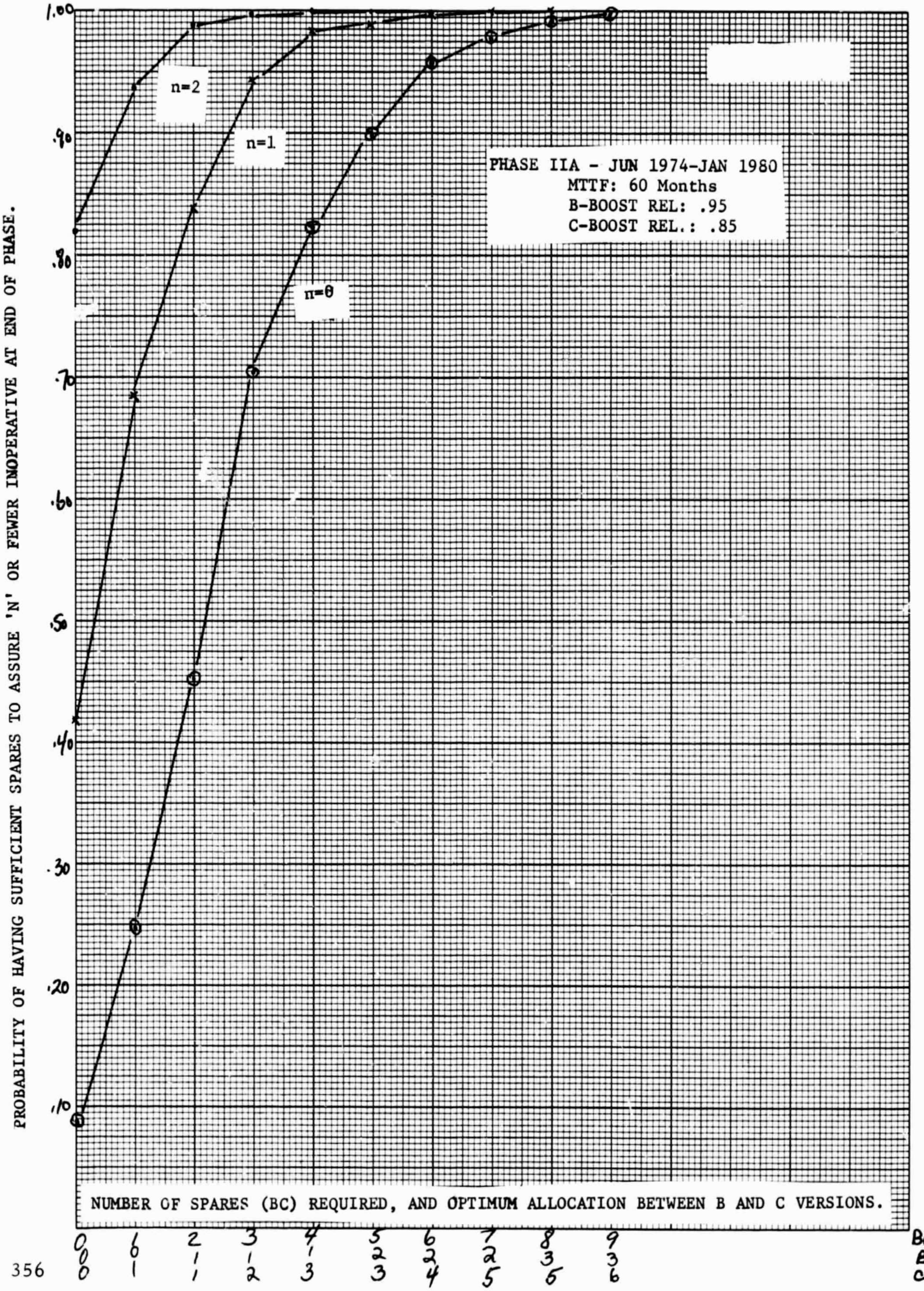

1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
n=2
n=1
n=0
PHASE IIA - JUN 1974-JAN 1980
MTTF: 60 Months
B-BOOST REL: .95
C-BOOST REL.: .85
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
BC 0 1 2 3 4 5 6 7 8 9
B 0 0 1 1 1 2 2 2 3 3
C 0 1 1 2 3 3 4 5 5 6

Figure D-10.

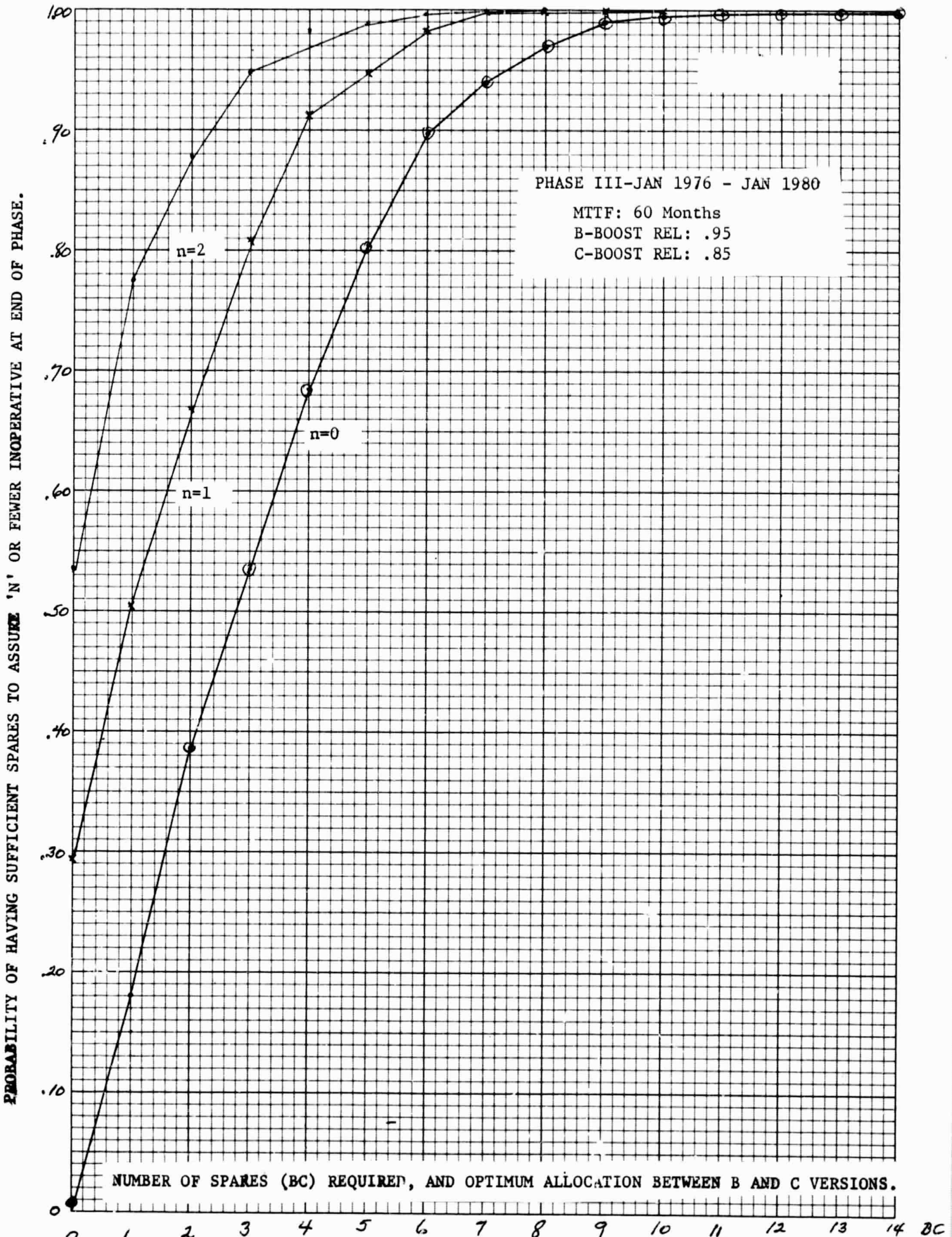
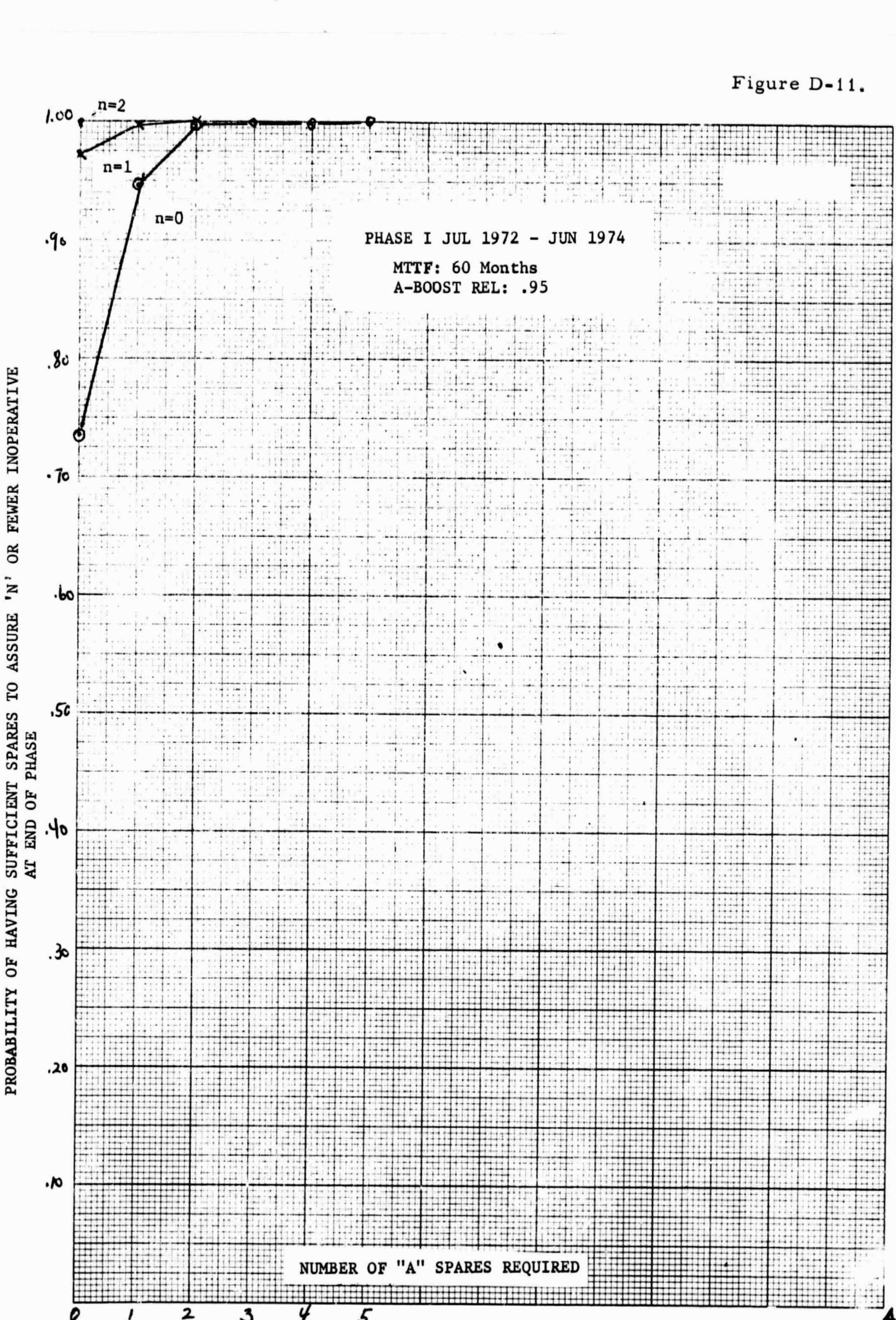
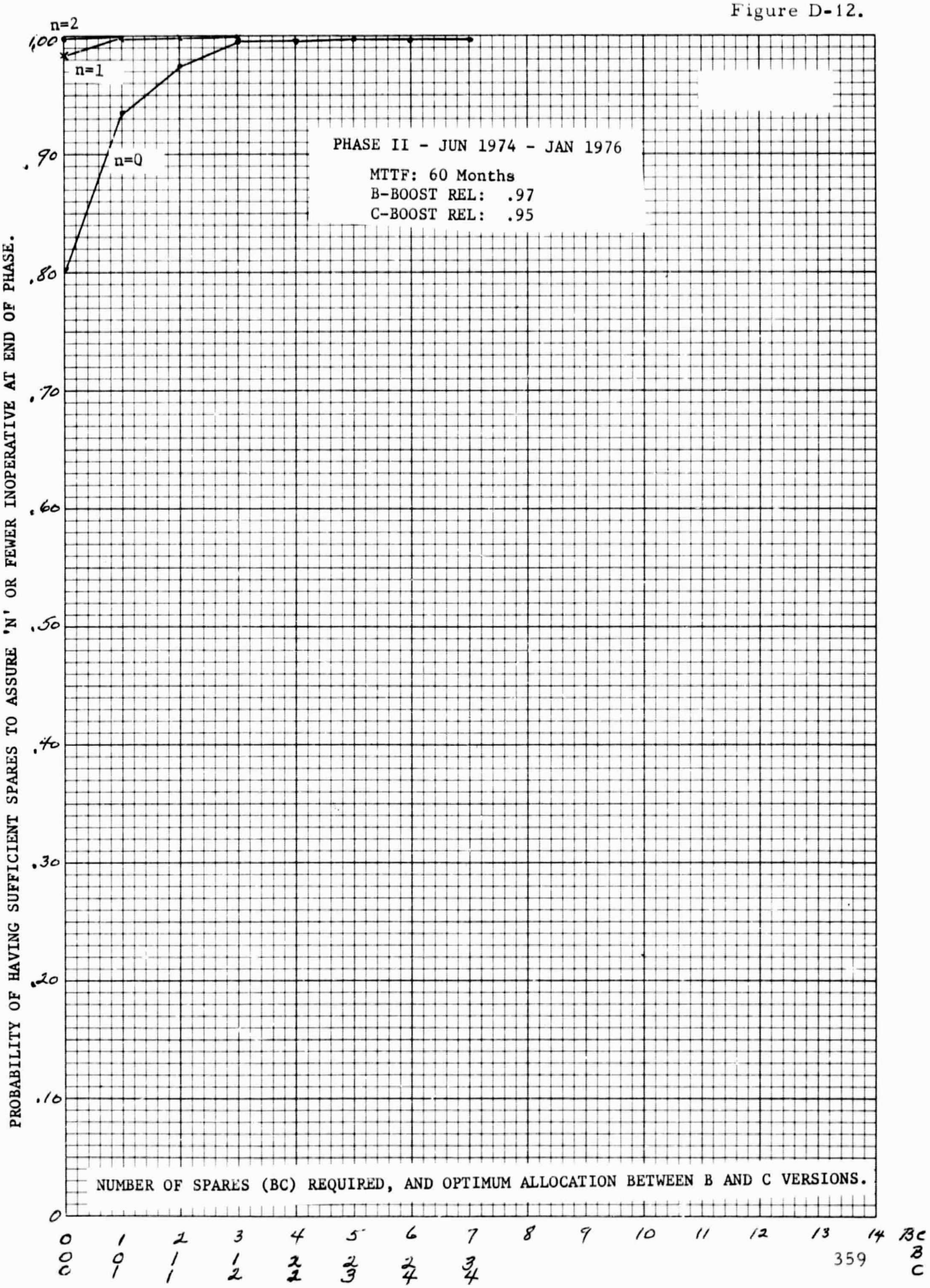

PHASE III-JAN 1976 - JAN 1980
MTTF: 60 Months
B-BOOST REL: .95
C-BOOST REL: .85
n=2
n=1
n=0
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
0 .10 .20 .30 .40 .50 .60 .70 .80 .90 1.00
BC 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
B 0 0 1 1 1 2 2 2 3 3 4 4 4 4 5
C 0 1 1 2 3 3 4 5 5 6 6 7 8 9 9

Figure D-11.



n=2
n=1
n=0
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
PHASE I JUL 1972 - JUN 1974
MTTF: 60 Months
A-BOOST REL: .95
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE
NUMBER OF "A" SPARES REQUIRED
0
1
2
3
4
5
A

Figure D-12.



PHASE II - JUN 1974 - JAN 1976
MTTF: 60 Months
B-BOOST REL: .97
C-BOOST REL: .95
n=2
n=1
n=0
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 BC
0 0 1 1 2 2 2 3 B
0 1 1 2 2 3 4 4 C

Figure D-13.

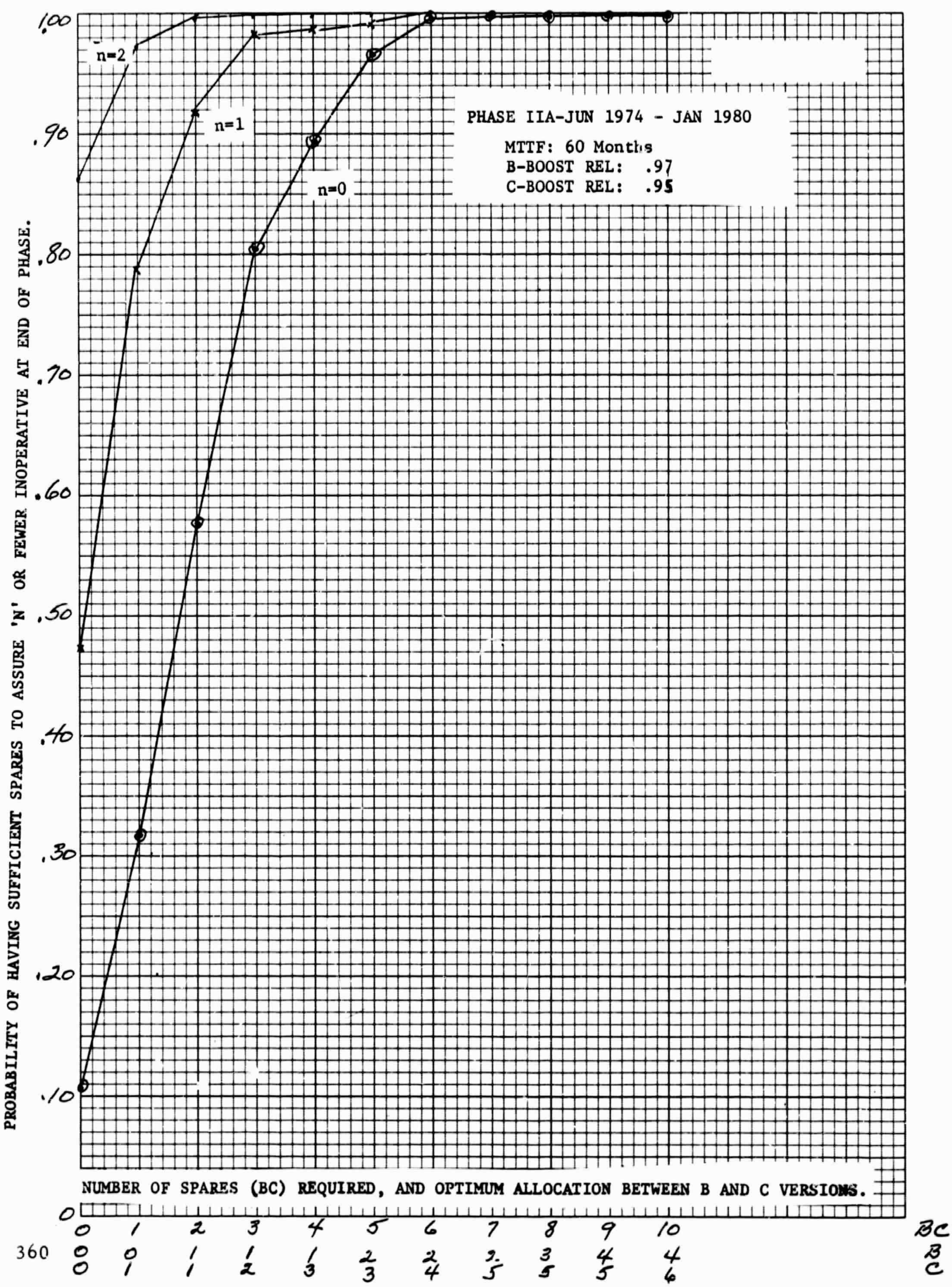

PHASE IIA-JUN 1974 - JAN 1980
MTTF: 60 Months
B-BOOST REL: .97
C-BOOST REL: .95
n=2
n=1
n=0
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
0 1 2 3 4 5 6 7 8 9 10 BC
0 0 1 1 1 2 2 2 3 4 4 B
0 1 1 2 3 3 4 5 5 5 6 C

Figure D-14.

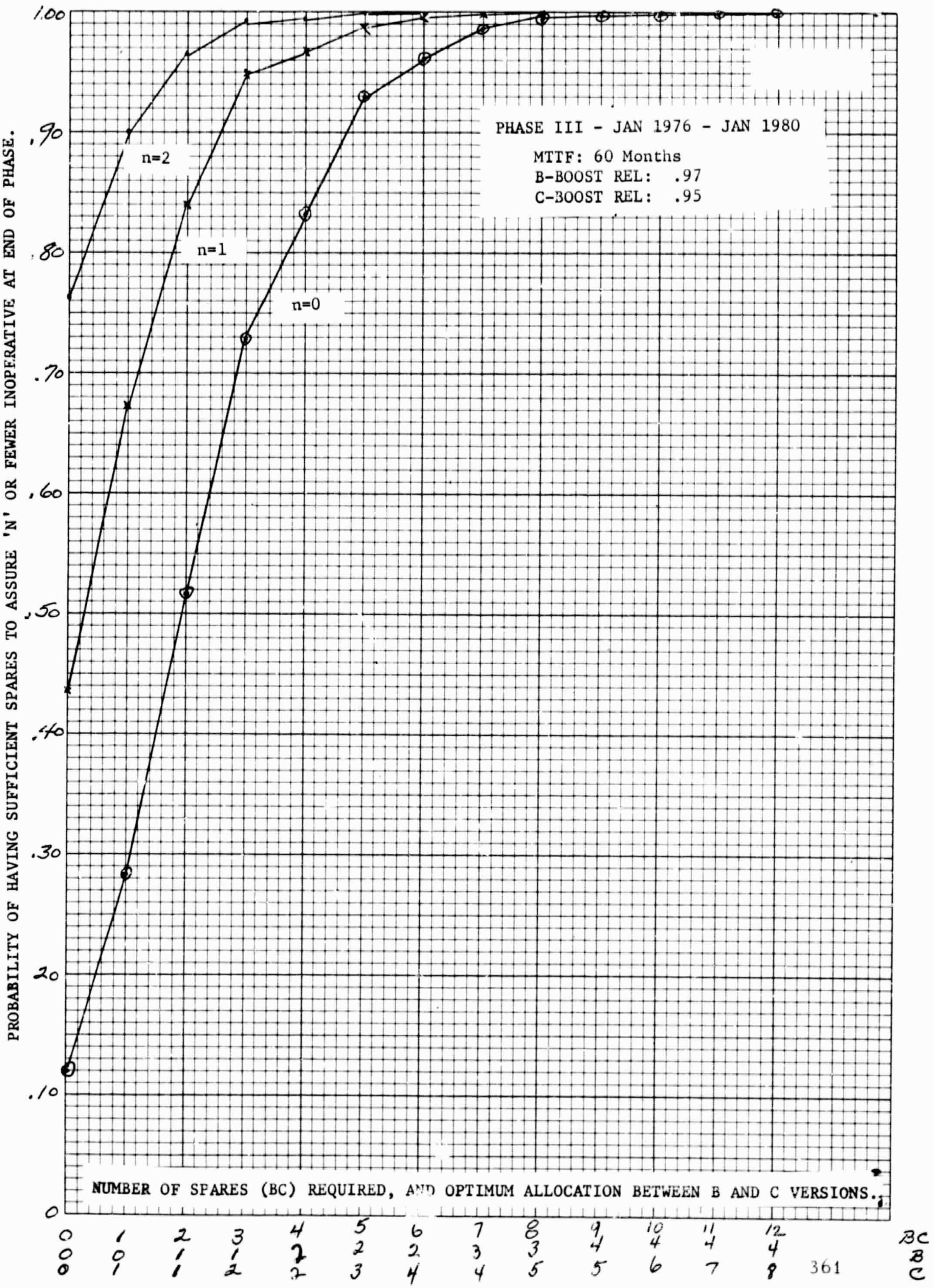
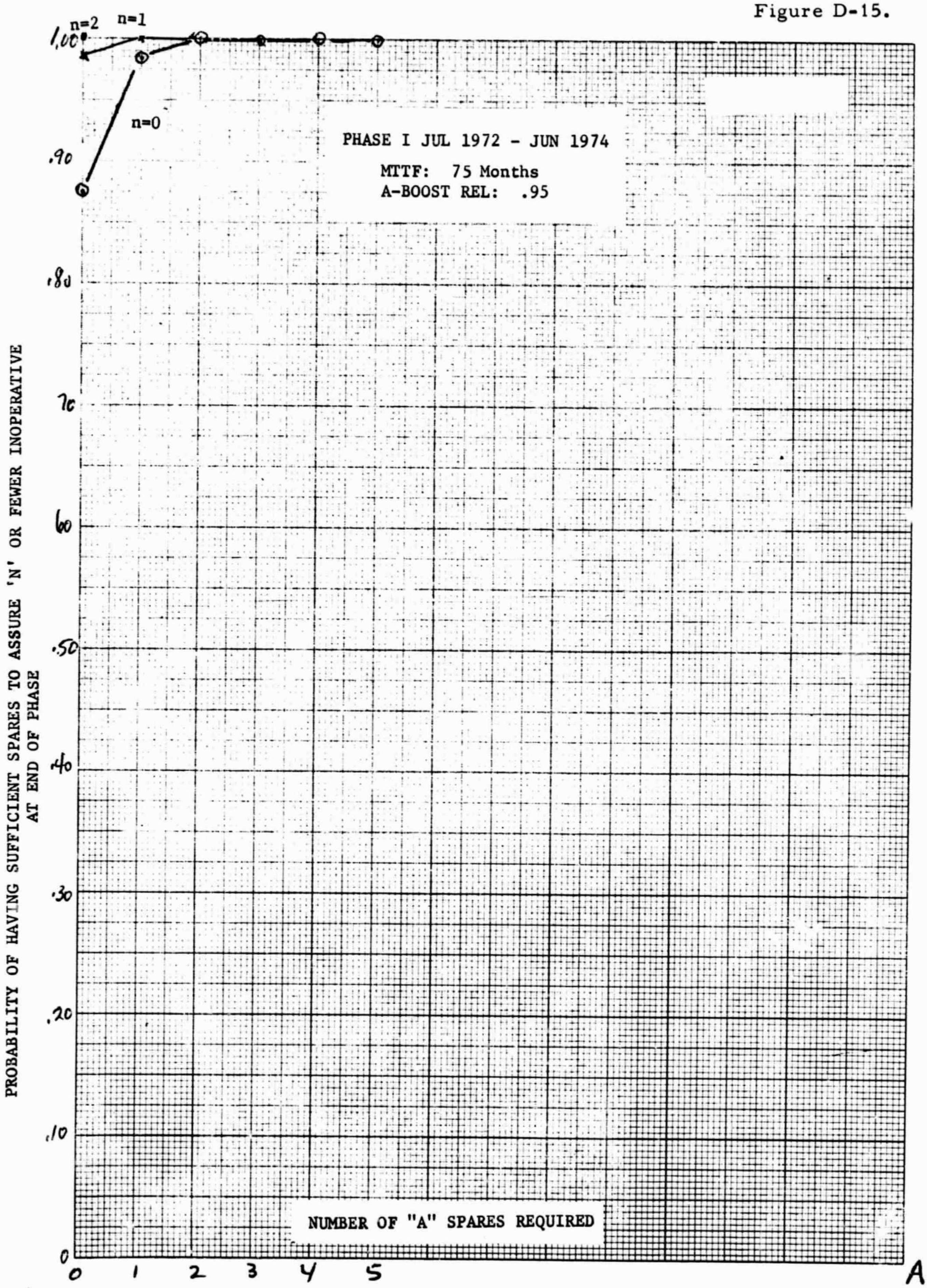

1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
PHASE III - JAN 1976 - JAN 1980
MTTF: 60 Months
B-BOOST REL: .97
C-BOOST REL: .95
n=2
n=1
n=0
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
0 1 2 3 4 5 6 7 8 9 10 11 12 BC
0 0 1 1 2 2 2 3 3 4 4 4 4 B
0 1 1 2 2 3 4 4 5 5 6 7 8 C

Figure D-15.



n=2
n=1
1.00
n=0
.90
PHASE I JUL 1972 - JUN 1974
MTTF: 75 Months
A-BOOST REL: .95
.80
.70
.60
.50
.40
.30
.20
.10
0
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE
NUMBER OF "A" SPARES REQUIRED
0
1
2
3
4
5
A

Figure D-16.

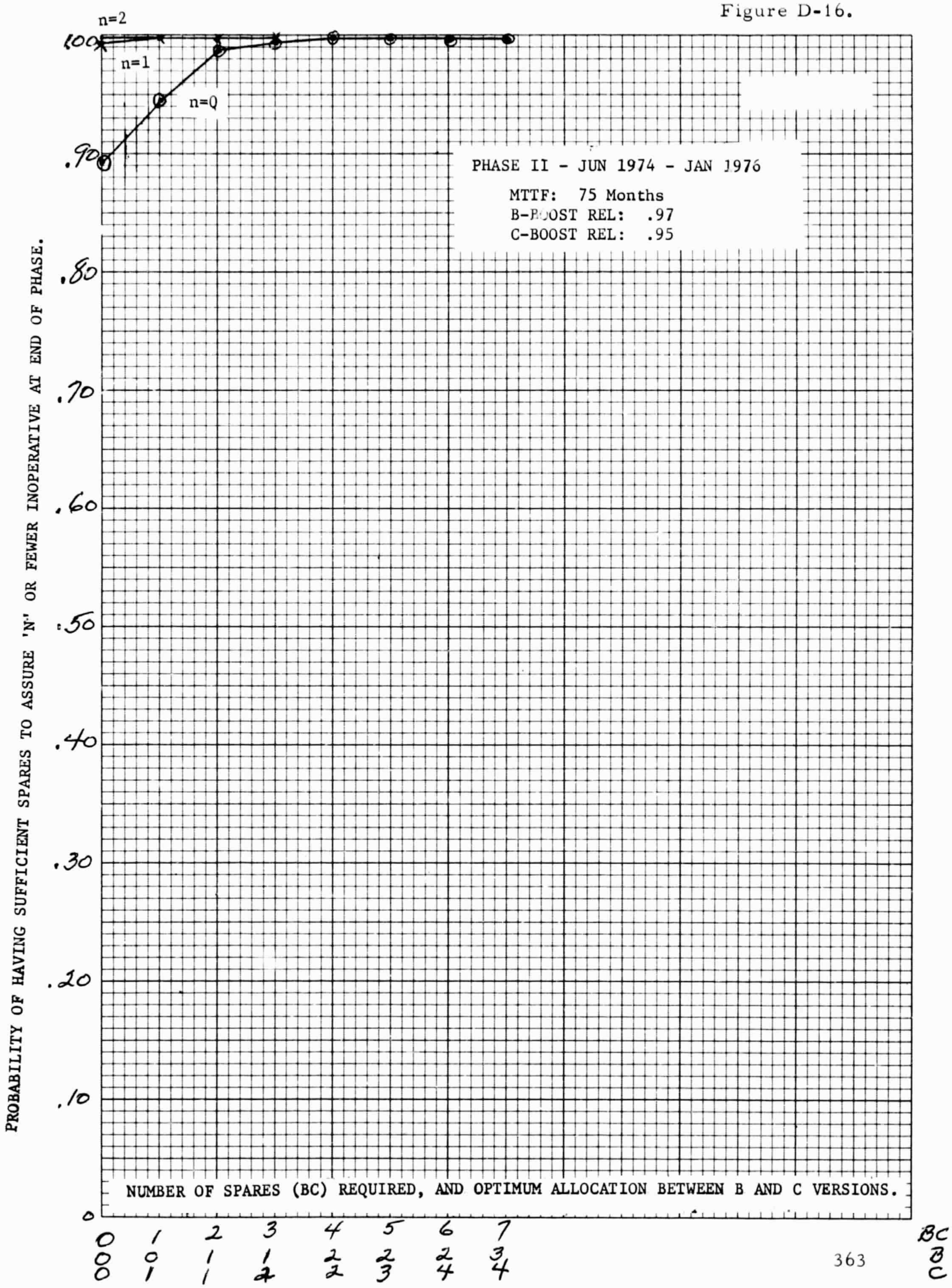

PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
PHASE II - JUN 1974 - JAN 1976
MTTF: 75 Months
B-BOOST REL: .97
C-BOOST REL: .95
n=2
n=1
n=0
100
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
BC 0 1 2 3 4 5 6 7
B 0 0 1 1 2 2 2 3
C 0 1 1 2 2 3 4 4

Figure D-17.

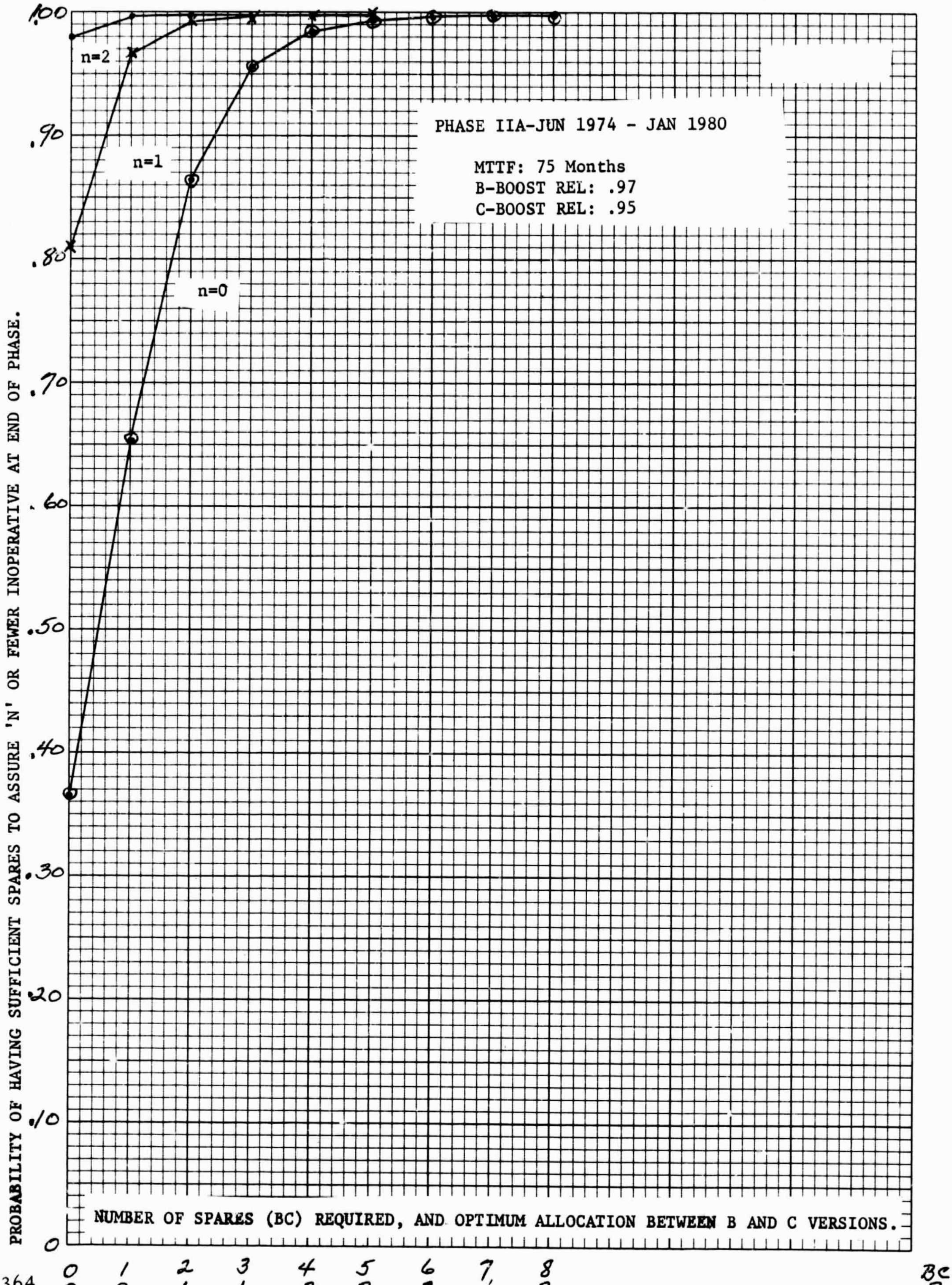
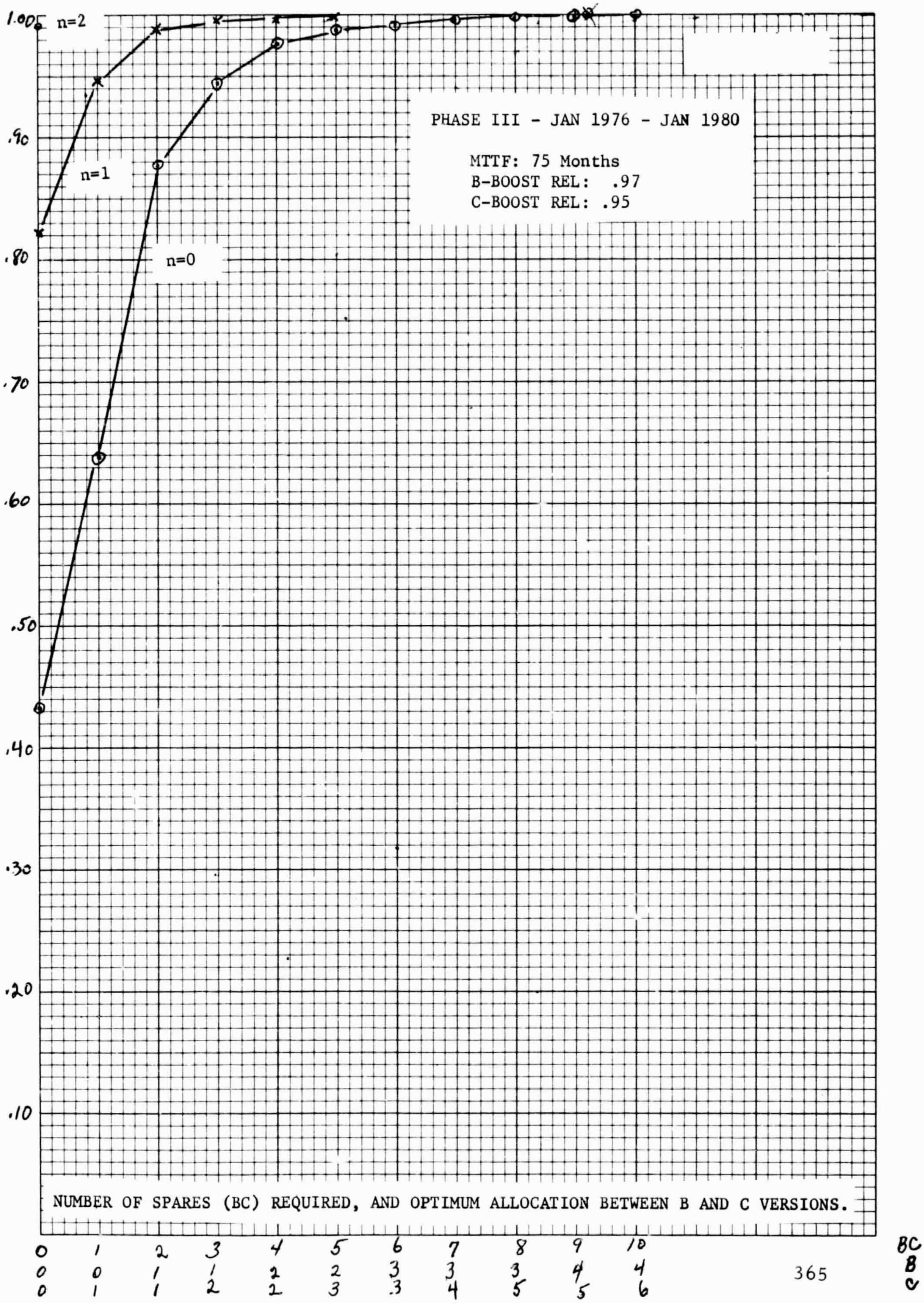

PHASE IIA-JUN 1974 - JAN 1980
MTTF: 75 Months
B-BOOST REL: .97
C-BOOST REL: .95
n=2
n=1
n=0
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
BC
B
C
0 0 0
1 0 1
2 1 1
3 1 2
4 2 2
5 3 2
6 3 3
7 4 3
8 3 5

Figure D-18.

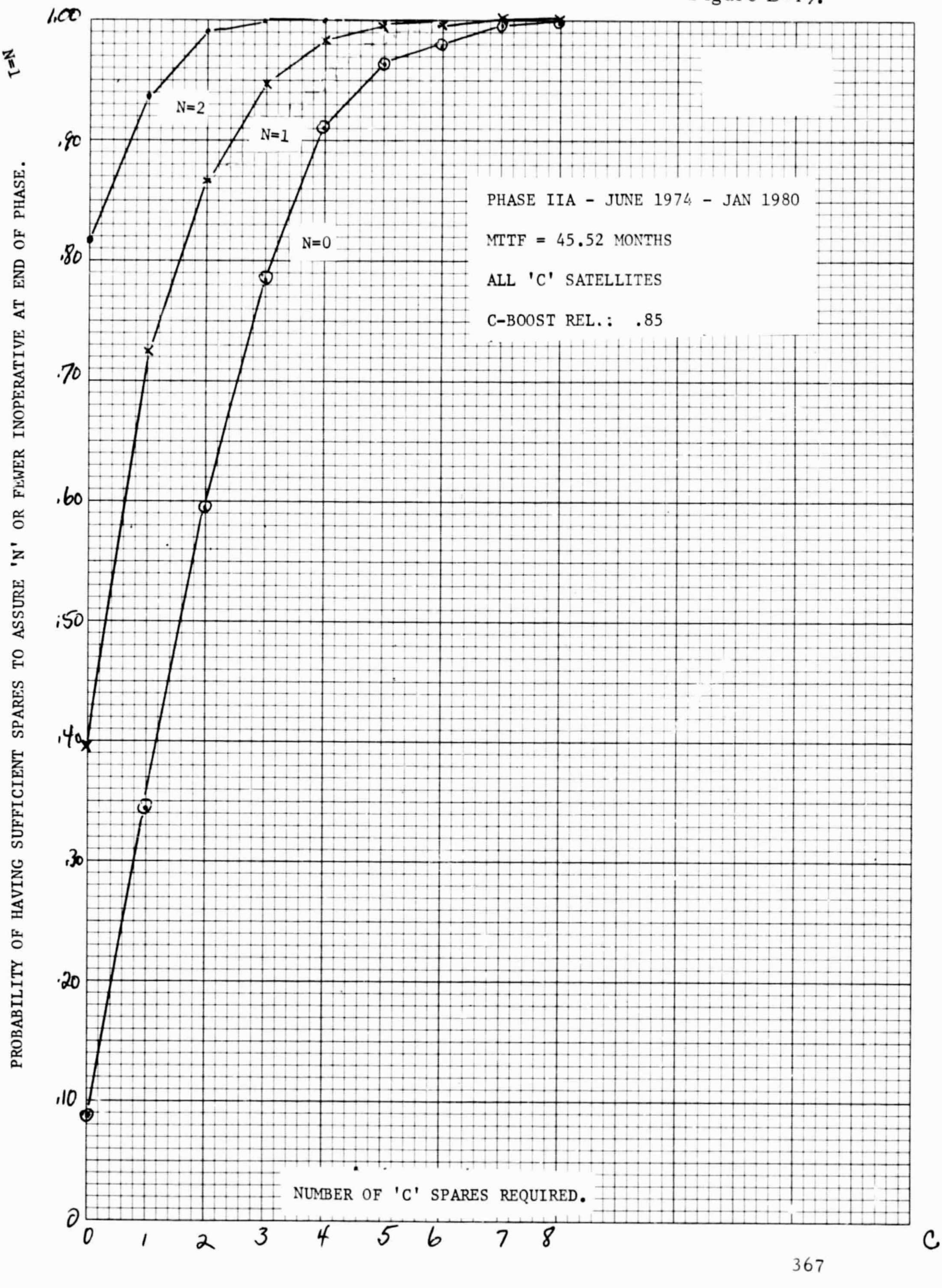

PHASE III - JAN 1976 - JAN 1980
MTTF: 75 Months
B-BOOST REL: .97
C-BOOST REL: .95
n=2
n=1
n=0
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF SPARES (BC) REQUIRED, AND OPTIMUM ALLOCATION BETWEEN B AND C VERSIONS.
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
BC 0 1 2 3 4 5 6 7 8 9 10
B 0 0 1 1 2 2 3 3 3 4 4
C 0 1 1 2 2 3 3 4 5 5 6

Finally, some advantage would be gained if B and C satellites were interchangeable. Then a given number of spare satellites could provide more efficient sparing of the active satellites. Probability of sufficient spares versus number of spares curves are given in Figures D-19 through D-20. The probability of having sufficient spares for a reduced Phase IA (July 1972 - July 1973) are given in Figure D-21.

5. CONCLUSIONS

The important conclusions of this study are summarized in Tables D-3 and D-4. In particular, the number and distribution of spares required to give 50%, 90%, and 99% probability that zero, one, and two satellites are inoperative at the end of each phase are given in Table D-3, and certain questions germane to the study are given and answered in Table D-4. Table D-4a presents the results when certain miscellaneous phase/configuration definitions are used. The "90% probability that no more than one satellite is inoperative" case was then used in the costing analysis.

Figure D-19.



N=1
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
N=2
N=1
N=0
PHASE IIA - JUNE 1974 - JAN 1980
MTTF = 45.52 MONTHS
ALL 'C' SATELLITES
C-BOOST REL.: .85
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF 'C' SPARES REQUIRED.
0
1
2
3
4
5
6
7
8
C

Figure D-20.

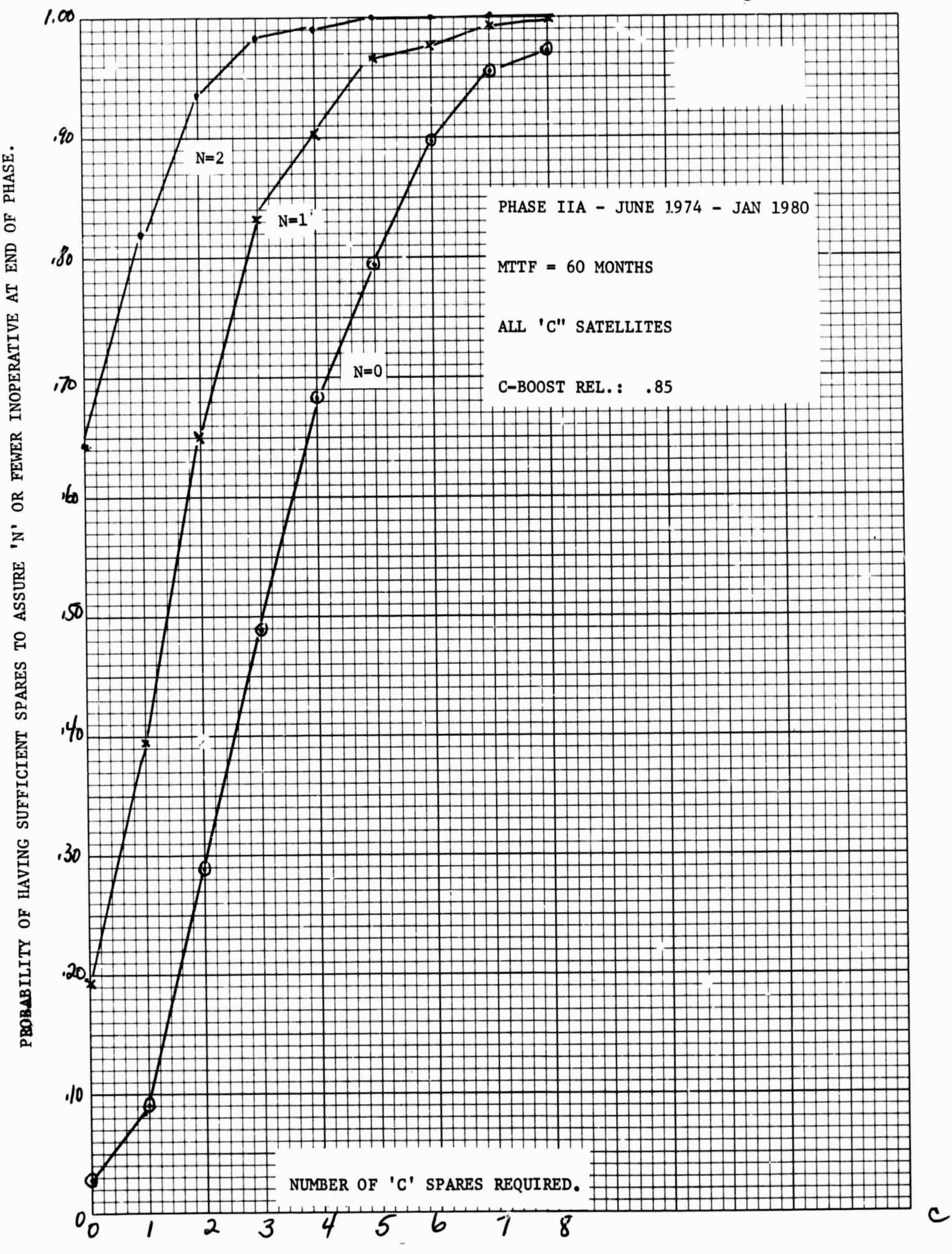

PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
N=2
N=1
N=0
PHASE IIA - JUNE 1974 - JAN 1980
MTTF = 60 MONTHS
ALL 'C" SATELLITES
C-BOOST REL.: .85
NUMBER OF 'C' SPARES REQUIRED.
0
1
2
3
4
5
6
7
8
C

Figure D-21.

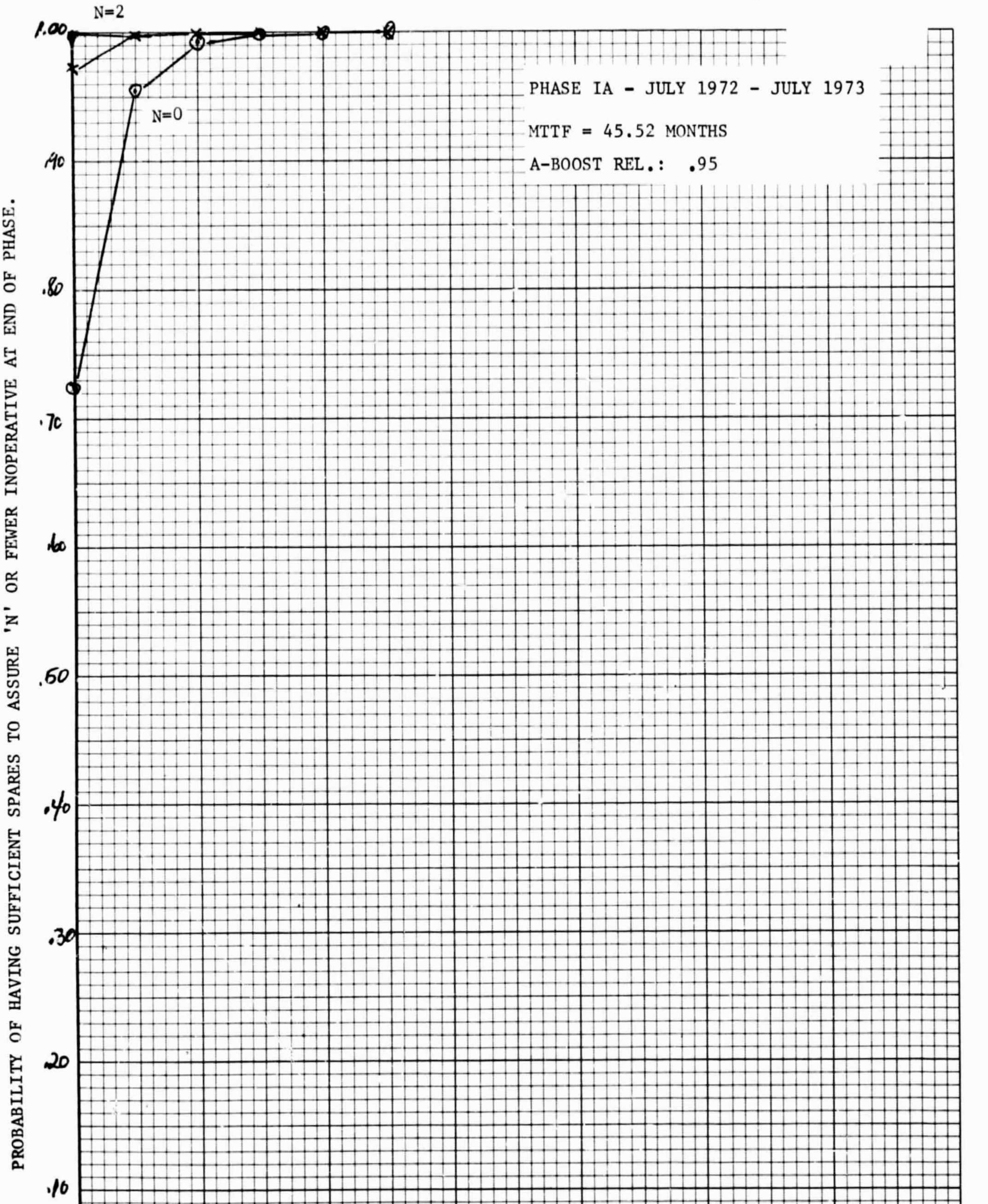

N=2
N=0
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
PHASE IA - JULY 1972 - JULY 1973
MTTF = 45.52 MONTHS
A-BOOST REL.: .95
PROBABILITY OF HAVING SUFFICIENT SPARES TO ASSURE 'N' OR FEWER INOPERATIVE AT END OF PHASE.
NUMBER OF 'A' SPARES REQUIRED.
0
1
2
3
4
5
6
7
8
A

Table D-3. Required Number of Spare Satellites for Phase I, II, IIA, and III To Give 50%, 90% and 99% Probability of Having a Specified Number (or less) Inoperative at the end of each phase.

		PROBABILITY OF HAVING:								
		ZERO INOPERATIVE			≤ ONE INOPERATIVE			≤ TWO INOPERATIVE		
		50%	90%	99%	50%	90%	99%	50%	90%	99%
MTTF = 45.52	Phase I	A=0	A=2	A=3	A=0	A=0	A=1	A=0	A=0	A=0
A-BOOST REL = .95	Phase II	0(0,0)*	3(1,2)	6(2,4)	0(0,0)	1(0,1)	3(1,2)	0(0,0)	0(0,0)	0(0,0)
B-BOOST REL = .95	Phase IIA	4(1,3)	8(3,5)	12(4,8)	2(1,1)	5(2,3)	7(2,5)	0(0,0)	2(1,1)	5(2,3)
C-BOOST REL = .85	Phase III	6(2,4)	10(3,7)	14(5,9)	3(1,2)	7(2,5)	11(4,7)	2(1,1)	5(2,3)	9(3,6)
MTTF = 60	Phase I	A=0	A=1	A=2	A=0	A=0	A=1	A=0	A=0	A=0
A-BOOST REL = .95	Phase II	0(0,0)	2(0,2)	5(4,1)	0(0,0)	0(0,0)	2(0,2)	0(0,0)	0(0,0)	0(0,0)
B-BOOST REL = .95	Phase IIA	3(1,2)	6(2,4)	8(3,5)	1(0,1)	3(1,2)	6(2,4)	0(0,0)	1(0,1)	3(1,2)
C-BOOST REL = .85	Phase III	3(1,2)	7(2,5)	9(3,6)	1(0,1)	4(1,3)	8(2,5)	0(0,0)	3(1,2)	6(2,4)
MTTF = 60	Phase I	A=0	A=1	A=2	A=0	A=0	A=1	A=0	A=0	A=0
A-BOOST REL = .95	Phase II	0(0,0)	1(0,1)	3(1,2)	0(0,0)	0(0,0	1(0,1)	0(0,0)	0(0,0)	0(0,0)
B-BOOST REL = .97	Phase IIA	2(1,1)	5(2,3)	6(2,4)	1(0,1)	2(1,1)	6(2,4)	0(0,0)	1(0,1)	2(1,1)
C-BOOST REL = .95	Phase III	2(1,1)	5(2,3)	8(3,5)	1(0,1)	3(1,2)	6(2,4)	0(0,0)	1(0,1)	3(1,2)
MTTF = 75	Phase I	A=0	A=1	A=2	A=0	A=0	A=1	A=0	A=0	A=0
A-BOOST REL = .95	Phase II	0(0,0)	1(0,1)	3(1,2)	0(0,0)	0(0,0)	0(0,0)	0(0,0)	0(0,0)	0(0,0)
B-BOOST REL = .97	Phase IIA	1(0,1)	3(1,2)	5(3,2)	0(0,0)	1(0,1)	2(1,1)	0(0,0)	0(0,0)	1(0,1)
C-BOOST REL = .95	Phase III	1(0,1)	3(1,2)	6(3,3)	0(0,0)	1(0,1)	3(1,2)	0(0,0)	1(0,1)	0(0,0)

*x(y,z) ≡ x = total spares, y = "B-spares", z = "C-spares", [Total (B,C)]

Table D-4. **Probability of having a fully operational system with certain spares strategies.**

	MTTF C-BOOST REL.	45.52 .86	60 .85	60 .95	75 .95
1. What is the probability that each phase can be completed without a single replacement launch?	Phase I	.51	.74	.74	.87
	Phase II	.50	.62	.80	.89
	Phase IIA	.02	.08	.11	.36
	Phase III	.01	.02	.12	.43
2. What is the probability that the system will be fully operational at the end of Phase II with one replacement satellite?	Phase II	.75	.84	.93	.95
3. What is the probability that the system will be fully operational at the end of Phase IIA with two replacement satellites?	Phase IIA	.08	.045	.58	.86
4. What is the probability that the system will be fully operational at the end of Phase III with three replacement satellites?	Phase III	.04	.53	.73	.94

Table D-4a. Required number of Spare Satellites for 3 Special Cases of Replenishment Schemes to give 50%, 90%, 99% Probability of Having a Specified Number (or less) Inoperative at the end of each phase.

		PROBABILITY OF HAVING:								
		Zero Inoperative			≤ Inoperative			≤ Two Inoperative		
		50%	90%	99%	50%	90%	99%	50%	90%	99%
MTTF = 45.52 Mo. C-Boost Rel. = .85 All C Satellites	Phase IIA	4	7	8	2	4	7	0	2	4
MTTF = 60 Mo. C-Boost Rel. = .85 All C Satellites	Phase IIA	2	4	7	1	3	6	0	1	2
MTTF = 45.52 Mo. A-Boost Rel. = .95	Phase IA	0	1	2	0	0	1	0	0	0

Foldout #1

Table D-5. PROBABILITY OF HAVING SUFFICIENT SPARES WITH A SATELLITE OF 45.52 MO. MTTF AND C BOOSTER RELIABILITY = .85

PRØBABILITY, P(N), ØF HAVING
'N' ØR FEWER SATELLITES INØPERA-
TIVE AT THE END ØF
PHASE I - JUL 1972-JUN 1974
WITH THE NUMBER ØF A-SPARES
DESIGNATED BELØW.

MTTF: 45.52
A-BØØST REL.: .95
================================

A	P(0)	P(1)	P(2)
-	----	----	----
0	.508	.914	1.000
1	.874	.992	1.000
2	.973	.999	1.000
3	.992	1.000	1.000
4	1.000	1.000	1.000
5	1.000	1.000	1.000

PRØBABILITY, P(N), ØF HAVING
'N' ØR FEWER SATELLITES INØPERA-

PRØBABILITY, P(N), ØF HAVING
'N' ØR FEWER SATELLITES INØPERA-
TIVE AT THE END ØF
PHASE IIA-JUN 1974-JAN 1980
WITH THE NUMBER ØF 'B-' AND
'C-SPARES DESIGNATED BELØW.

MTTF: 45.52
B-BØØST REL: .95
C-BØØST REL: .85
================================

B	C	BC	P(0)	P(1)	P(2)
-	-	--	----	----	----
0	0	0	.025	.204	.644
0	1	1	.085	.411	.812
0	2	2	.169	.639	.927
0	3	3	.238	.803	.972
0	4	4	.290	.919	.992
0	5	5	.308	.960	.997
0	6	6	.318	.982	.999
0	7	7	.323	.992	.999
0	8	8	.325	.996	.999
1	0	1	.054	.360	.851
1	1	2	.188	.592	.922
1	2	3	.371	.786	.970
1	3	4	.523	.893	.986
1	4	5	.637	.959	.997
1	5	6	.678	.980	.999
1	6	7	.700	.991	.999
1	7	8	.711	.996	.999

PRØBABILITY, P(N), ØF HAVING
'N' ØR FEWER SATELLITES INØPERA-
TIVE AT THE END ØF
PHASE III-JAN 1976-JAN 1980
WITH THE NUMBER ØF 'B-' AND
'C-SPARES DESIGNATED BELØW.

MTTF: 45.52
B-BØØST REL: .95
C-BØØST REL: .85
================================

B	C	BC	P(0)	P(1)	P(2)
-	-	--	----	----	----
0	0	0	.012	.091	.301
0	1	1	.044	.206	.474
0	2	2	.093	.361	.654
0	3	3	.135	.485	.782
0	4	4	.165	.573	.875
0	5	5	.195	.652	.938
0	6	6	.210	.690	.969
0	7	7	.219	.714	.988
0	8	8	.224	.725	.996
0	9	9	.225	.729	.999
0	10	10	.226	.730	.999
1	0	1	.030	.177	.465
1	1	2	.109	.339	.631
1	2	3	.232	.525	.773
1	3	4	.338	.662	.864
1	4	5	.411	.764	.931
1	5	6	.487	.838	.964
1	6	7	.524	.874	.984
1	7	8	.547	.895	.994
1	8	9	.558	.905	.997
1	9	10	.562	.908	.999
1	10	11	.563	.909	.999
2	0	2	.044	.239	.575

PRØBABILITY, P(N), ØF HAVING
'N' ØR FEWER SATELLITES INØPERA-
TIVE AT THE END ØF
PHASE II-JUN 1974-JAN 1976
WITH THE NUMBER ØF 'B-' AND
'C-SPARES DESIGNATED BELØW.

MTTF: 45.52
B-BØØST REL: .95
C-BØØST REL: .85
==================================

B	C	BC	P(0)	P(1)	P(2)
0	0	0	.500	.886	.991
0	1	1	.753	.969	.998
0	2	2	.842	.995	.999
0	3	3	.863	.998	.999
0	4	4	.871	.999	.999
1	0	1	.567	.928	.999
1	1	2	.853	.984	.999
1	2	3	.953	.999	.999
1	3	4	.978	.999	.999
1	4	5	.987	.999	.999
2	0	2	.572	.931	.999
2	1	3	.860	.985	.999
2	2	4	.962	.999	.999
2	3	5	.987	.999	.999
2	4	6	.996	.999	.999
1	4	5	.657	.959	.997
1	5	6	.678	.980	.999
1	6	7	.700	.991	.999
1	7	8	.711	.996	.999
1	8	9	.715	.998	.999
2	0	2	.071	.448	.969
2	1	3	.246	.694	.984
2	2	4	.486	.870	.994
2	3	5	.685	.944	.998
2	4	6	.834	.982	.999
2	5	7	.887	.992	.999
2	6	8	.917	.997	.999
2	7	9	.931	.998	.999
2	8	10	.936	.999	.999
3	0	3	.074	.466	.994
3	1	4	.258	.715	.997
3	2	5	.510	.887	.999
3	3	6	.719	.955	.999
3	4	7	.875	.987	.999
3	5	8	.932	.994	.999
3	6	9	.962	.998	.999
3	7	10	.977	.999	.999
3	8	11	.983	.999	.999
4	0	4	.075	.470	.999
4	1	5	.260	.720	.999
4	2	6	.515	.891	.999
4	3	7	.727	.958	.999
4	4	8	.884	.988	.999
4	5	9	.941	.995	.999
4	6	10	.972	.998	.999
4	7	11	.987	.999	.999
4	8	12	.993	.999	.999
5	0	5	.075	.471	.999
5	1	6	.261	.721	.999
5	2	7	.515	.892	.999
5	3	8	.727	.958	.999
5	4	9	.885	.988	.999
5	5	10	.942	.995	.999
5	6	11	.973	.998	.999
5	7	12	.988	.999	.999
5	8	13	.994	.999	.999
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	8	9	.558	.905	.997
1	9	10	.562	.908	.999
1	10	11	.563	.909	.999
2	0	2	.044	.239	.575
2	1	3	.159	.427	.731
2	2	4	.339	.623	.846
2	3	5	.492	.759	.914
2	4	6	.598	.862	.961
2	5	7	.709	.924	.978
2	6	8	.764	.952	.992
2	7	9	.797	.970	.997
2	8	10	.814	.977	.999
2	9	11	.820	.980	.999
2	10	12	.820	.981	.999
3	0	3	.051	.268	.624
3	1	4	.183	.466	.775
3	2	5	.391	.663	.877
3	3	6	.568	.794	.934
3	4	7	.690	.896	.973
3	5	8	.818	.950	.983
3	6	9	.881	.974	.995
3	7	10	.920	.988	.999
3	8	11	.939	.994	.999
3	9	12	.945	.996	.999
3	10	13	.946	.997	.999
4	0	4	.053	.276	.638
4	1	5	.190	.477	.786
4	2	6	.405	.673	.885
4	3	7	.589	.802	.939
4	4	8	.716	.904	.976
4	5	9	.849	.954	.984
4	6	10	.914	.976	.996
4	7	11	.954	.990	.999
4	8	12	.974	.995	.999
4	9	13	.981	.997	.999
4	10	14	.982	.998	.999
5	0	5	.054	.279	.642
5	1	6	.192	.480	.790
5	2	7	.410	.676	.888
5	3	8	.596	.805	.941
5	4	9	.724	.906	.976
5	5	10	.859	.956	.985
5	6	11	.924	.978	.996
5	7	12	.965	.991	.999
5	8	13	.985	.996	.999
5	9	14	.992	.998	.999
5	10	15	.993	.999	.999

Foldout# 2

Table D-5.

Foldout #1

PRECEDING PAGE BLANK NOT FILMED

Table D-6. PROBABILITY OF HAVING SUFFICIENT SPARES WITH A SATELLITE OF 60 MO. MTTF AND C BOOSTER RELIABILITY = .85

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERATIVE AT THE END ØF PHASE I - JUL 1972-JUN 1974 WITH THE NUMBER ØF A-SPARES DESIGNATED BELØW.

MTTF: 60
A-BØØST REL.: .95

A	P(0)	P(1)	P(2)
0	.736	.972	1.000
1	.946	.996	1.000
2	.996	1.000	1.000
3	.998	1.000	1.000
4	1.000	1.000	1.000
5	1.000	1.000	1.000

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERATIVE AT THE END ØF PHASE II-JUN 1974-JAN 1976 WITH THE NUMBER ØF 'B-' AND 'C-SPARES DESIGNATED BELØW.

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERATIVE AT THE END ØF PHASE IIA-JUN 1974-JAN 1980 WITH THE NUMBER ØF 'B-' AND 'C-SPARES DESIGNATED BELØW.

MTTF: 60
B-BØØST REL: .95
C-BØØST REL: .85

B	C	BC	P(0)	P(1)	P(2)

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERATIVE AT THE END ØF PHASE III-JAN 1976-JAN 1980 WITH THE NUMBER ØF 'B-' AND 'C-SPARES DESIGNATED BELØW.

MTTF: 60
B-BØØST REL: .95
C-BØØST REL: .85

B	C	BC	P(0)	P(1)	P(2)
0	0	0	.066	.294	.535
0	1	1	.180	.503	.776
0	2	2	.284	.664	.884
0	3	3	.363	.784	.953
0	4	4	.407	.843	.983
0	5	5	.425	.867	.995
0	6	6	.434	.877	.998
0	7	7	.435	.878	.999
0	8	8	.436	.879	.999
0	9	9	.436	.879	.999
1	0	1	.124	.452	.624
1	1	2	.338	.669	.879
1	2	3	.535	.809	.949
1	3	4	.684	.913	.981
1	4	5	.766	.957	.993
1	5	6	.800	.973	.999

WITH THE NUMBER ØF 'B-' AND
'C-SPARES DESIGNATED BELØW.

MTTF: 60
B-BØØST REL: .95
C-BØØST REL: .85

B	C	BC	P(0)	P(1)	P(2)
0	0	0	.614	.937	.997
0	1	1	.844	.981	.999
0	2	2	.904	.996	.999
0	3	3	.924	.999	.999
0	4	4	.930	.999	.999
1	0	1	.656	.957	.999
1	1	2	.903	.987	.999
1	2	3	.967	.998	.999
1	3	4	.989	.999	.999
1	4	5	.995	.999	.999
2	0	2	.658	.958	.999
2	1	3	.906	.987	.999
2	2	4	.970	.998	.999
2	3	5	.992	.999	.999
2	4	6	.998	.999	.999
3	0	3	.659	.958	.999
3	1	4	.907	.987	.999
3	2	5	.971	.998	.999
3	3	6	.993	.999	.999
3	4	7	.999	.999	.999

B	C	BC	P(0)	P(1)	P(2)
0	0	0	.088	.419	.830
0	1	1	.247	.684	.936
0	2	2	.386	.870	.980
0	3	3	.451	.951	.995
0	4	4	.481	.985	.998
0	5	5	.491	.996	.999
0	6	6	.494	.999	.999
1	0	1	.161	.616	.967
1	1	2	.451	.836	.988
1	2	3	.705	.943	.996
1	3	4	.823	.982	.999
1	4	5	.879	.995	.999
1	5	6	.896	.998	.999
1	6	7	.901	.999	.999
2	0	2	.176	.656	.995
2	1	3	.492	.867	.998
2	2	4	.769	.957	.999
2	3	5	.897	.989	.999
2	4	6	.958	.997	.999
2	5	7	.977	.999	.999
2	6	8	.983	.999	.999
3	0	3	.178	.663	.999
3	1	4	.499	.872	.999
3	2	5	.780	.959	.999
3	3	6	909	.990	.999
3	4	7	.971	.997	.999
3	5	8	.990	.999	.999
3	6	9	.996	.999	.999

1	4	5	.766	.957	.993
1	5	6	.800	.973	.999
1	6	7	.817	.978	.999
1	7	8	.819	.979	.999
1	8	9	.820	.979	.999
1	9	10	.821	.979	.999
2	0	2	.146	.509	.651
2	1	3	.397	.724	.912
2	2	4	.629	.852	.970
2	3	5	.803	.947	.989
2	4	6	.899	.984	.996
2	5	7	.940	.996	.999
2	6	8	.959	.999	.999
2	7	9	.962	.999	.999
2	8	10	.963	.999	.999
2	9	11	.964	.999	.999
3	0	3	.150	.520	.655
3	1	4	.410	.734	.918
3	2	5	.649	.859	.973
3	3	6	.829	.951	.990
3	4	7	.928	.986	.996
3	5	8	.970	.997	.999
3	6	9	.990	.999	.999
3	7	10	.993	.999	.999
3	8	11	.994	.999	.999
3	9	12	.995	.999	.999
4	0	4	.151	.522	.656
4	1	5	.412	.736	.919
4	2	6	.652	.860	.974
4	3	7	.833	.952	.990
4	4	8	.933	.986	.996
4	5	9	.975	.997	.999
4	6	10	.995	.999	.999
4	7	11	.998	.999	.999
4	8	12	.999	.999	.999
4	9	13	.999	.999	.999
5	0	5	.151	.522	.656
5	1	6	.412	.736	.919
5	2	7	.652	.860	.974
5	3	8	.833	.952	.990
5	4	9	.933	.986	.996
5	5	10	.975	.997	.999
5	6	11	.995	.999	.999
5	7	12	.998	.999	.999
5	8	13	.999	.999	.999
5	9	14	.999	.999	.999

Foldout #2

Table D-6.

Foldout #1

Table D-7. PROBABILITY OF HAVING SUFFICIENT SPARES WITH A SATELLITE OF 60 MO. MTTF AND C BOOSTER RELIABILITY = .95

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERATIVE AT THE END ØF PHASE I - JUL 1972-JUN 1974 WITH THE NUMBER ØF A-SPARES DESIGNATED BELØW.

MTTF: 60
A-BØØST REL.: .95

A	P(0)	P(1)	P(2)
0	.736	.972	1.000
1	.946	.996	1.000
2	.996	1.000	1.000
3	.998	1.000	1.000
4	1.000	1.000	1.000
5	1.000	1.000	1.000

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERATIVE AT THE END ØF PHASE II -JUN 1974-JAN 1976 WITH THE NUMBER ØF B-SPARES DESIGNATED BELØW.

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERATIVE AT THE END ØF PHASE IIA-JUN 1974-JAN 1980 WITH THE NUMBER ØF 'B-' AND 'C-SPARES DESIGNATED BELØW.

MTTF: 60
B-BØØST REL: .97
C-BØØST REL: .95

B	C	BC	P(0)	P(1)	P(2)
0	0	0	.108	.472	.864
0	1	1	.319	.788	.971
0	2	2	.443	.934	.996
0	3	3	.491	.980	.990
0	4	4	.504	.998	.999
0	5	5	.506	.999	.999
0	6	6	.506	.999	.999
1	0	1	.196	.683	.978
1	1	2	.579	.917	.995
1	2	3	.804	.983	.999

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERATIVE AT THE END ØF PHASE III-JAN 1976-JAN 1980 WITH THE NUMBER ØF 'B-' AND 'C-SPARES DESIGNATED BELØW.

MTTF: 60
B-BØØST REL: .97
C-BØØST REL: .95

B	C	BC	P(0)	P(1)	P(2)
0	0	0	.120	.435	.761
0	1	1	.281	.672	.900
0	2	2	.394	.818	.972
0	3	3	.441	.872	.992
0	4	4	.455	.888	.998
0	5	5	.459	.892	.999
0	6	6	.460	.893	.999
0	7	7	.460	.893	.999
0	8	8	.460	.893	.999
0	9	9	.460	.893	.999
1	0	1	.222	.633	.896
1	1	2	.519	.840	.966
1	2	3	.727	.950	.993
1	3	4	.813	.982	.999
1	4	5	.841	.991	.999
1	5	6	.847	.994	.999
1	6	7	.848	.994	.999
1	7	8	.849	.994	.999
1	8	9	.849	.994	.999

DESIGNATED BELOW.

PRØBABILITY, P(N), ØF HAVING
'N' ØR FEWER SATELLITES INØPERA-
TIVE AT THE END ØF
PHASE II-JUN 1974-JAN 1976
WITH THE NUMBER ØF 'B-' AND
'C-SPARES DESIGNATED BELØW.

MTTF: 60
B-BØØST REL: .97
C-BØØST REL: .95
==============================

B	C	BC	P(0)	P(1)	P(2)
0	0	0	.801	.984	.999
0	1	1	.933	.999	.999
0	2	2	.955	.999	.999
0	3	3	.955	.999	.999
0	4	4	.956	.999	.999
1	0	1	.835	.990	.999
1	1	2	.972	.999	.999
1	2	3	.995	.999	.999
1	3	4	.995	.999	.999
1	4	5	.996	.999	.999
2	0	2	.838	.991	.999
2	1	3	.976	.999	.999
2	2	4	.999	.999	.999
2	3	5	.999	.999	.999
2	4	6	.999	.999	.999
3	0	3	.838	.991	.999
3	1	4	.976	.999	.999
3	2	5	.999	.999	.999
3	3	6	.999	.999	.999
3	4	7	.999	.999	.999

Foldout #2

0	6	6	.506	.999	.999
1	0	1	.196	.683	.978
1	1	2	.579	.917	.995
1	2	3	.804	.983	.999
1	3	4	.892	.988	.990
1	4	5	.915	.999	.999
1	5	6	.919	.999	.999
1	6	7	.919	.999	.999
2	0	2	.212	.722	.999
2	1	3	.628	.941	.999
2	2	4	.872	.992	.999
2	3	5	.968	.989	.990
2	4	6	.993	.999	.999
2	5	7	.997	.999	.999
2	6	8	.997	.999	.999
3	0	3	.213	.723	.999
3	1	4	.629	.941	.999
3	2	5	.873	.992	.999
3	3	6	.969	.989	.990
3	4	7	.994	.999	.999
3	5	8	.998	.999	.999
3	6	9	.998	.999	.999
4	0	4	.213	.724	.999
4	1	5	.630	.942	.999
4	2	6	.875	.992	.999
4	3	7	.971	.989	.990
4	4	8	.996	.999	.999
4	5	9	.999	.999	.999
4	6	10	.999	.999	.999

1	5	6	.847	.994	.999
1	6	7	.848	.994	.999
1	7	8	.849	.994	.999
1	8	9	.849	.994	.999
1	9	10	.849	.994	.999
2	0	2	.253	.687	.926
2	1	3	.593	.875	.978
2	2	4	.831	.967	.996
2	3	5	.930	.989	.999
2	4	6	.961	.995	.999
2	5	7	.969	.997	.999
2	6	8	.970	.997	.999
2	7	9	.971	.997	.999
2	8	10	.971	.997	.999
2	9	11	.971	.997	.999
3	0	3	.260	.699	.933
3	1	4	.609	.883	.981
3	2	5	.853	.972	.997
3	3	6	.954	.992	.999
3	4	7	.986	.997	.999
3	5	8	.994	.999	.999
3	6	9	.995	.999	.999
3	7	1[illegible]	.996	.999	.999
3	8	[illegible]	.996	.99[illegible]	.999
3	9	12	.996	.999	.999
4	0	4	.261	.701	.934
4	1	5	.610	.885	.982
4	2	6	.855	.973	.997
4	3	7	.957	.993	.999
4	4	8	.989	.998	.999
4	5	9	.997	.999	.999
4	6	10	.998	.999	.999
4	7	11	.999	.999	.999
4	8	12	.999	.999	.999
4	9	13	.999	.999	.999
5	0	5	.261	.701	.934
5	1	6	.611	.885	.982
5	2	7	.856	.973	.997
5	3	8	.958	.993	.999
5	4	9	.990	.998	.999
5	5	10	.998	.999	.999
5	6	11	.999	.999	.999
5	7	12	.999	.999	.999
5	8	13	.999	.999	.999
5	9	14	.999	.999	.999

Table D-7.

Foldout #1

PRECEDING PAGE BLANK NOT FILMED.

Table D-8. PROBABILITY OF HAVING SUFFICIENT SPARES WITH A SATELLITE OF 75 MO. MTTF AND C BOOSTER RELIABILITY=.95

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERA-TIVE AT THE END ØF
PHASE I - JUL 1972-JUN 1974
WITH THE NUMBER ØF A-SPARES DESIGNATED BELØW.

MTTF: 75
A-BØØST REL.: .95

A	P(0)	P(1)	P(2)
0	.874	.986	1.00C
1	.984	1.000	1.00C
2	1.000	1.000	1.000
3	1.000	1.000	1.0CC
4	1.000	1.000	1.000
5	1.000	1.0CC	1.000

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERA-TIVE AT THE END ØF
PHASE IIA-JUN 1974-JAN-1980
WITH THE NUMBER ØF 'B-' AND 'C-SPARES DESIGNATED BELØW.

MTTF: 75
B-BØØST REL: .97
C-BØØST REL: .95

B	C	BC	P(0)	P(1)	P(2)
0	0	0	.366	.810	.980
0	1	1	.652	.968	.999
0	2	2	.723	.998	.999
0	3	3	.727	.999	.999
0	4	4	.727	.999	.999
0	5	5	.728	.999	.999
0	6	6	.728	.999	.999
0	7	7	.728	.999	.999

PRØBABILITY, P(N), ØF HAVING 'N' ØR FEWER SATELLITES INØPERA-TIVE AT THE END ØF
PHASE III-JAN 1976-JAN 1980
WITH THE NUMBER ØF 'B-' AND 'C-SPARES DESIGNATED BELØW.

MTTF: 75
B-BØØST REL: .97
C-BØØST REL: .95

B	C	BC	P(0)	P(1)	P(2)
C	0	0	.432	.821	.999
0	1	1	.638	.948	.999
0	2	2	.685	.970	.999
0	3	3	.693	.975	.999
0	4	4	.695	.977	.999
0	5	5	.696	.977	.999
0	6	6	.696	.977	.999
0	7	7	.696	.977	.999
0	8	8	.696	.977	.999
1	0	1	.596	.916	.990
1	1	2	.878	.988	.999
1	2	3	.944	.995	.999
1	3	4	.954	.998	.999
1	4	5	.958	.999	.999

5			1.000	1.000	1.000

PRØBABILITY, P(N), ØF HAVING
'N' ØR FEWER SATELLITES INØPERA-
TIVE AT THE END ØF
PHASE II-JUN 1974-JAN 1976
WITH THE NUMBER ØF 'B-' AND
'C-SPARES DESIGNATED BELØW.

MTTF: 75
B-BØØST REL: .97
C-BØØST REL: .95
==================================

B	C	BC	P(0)	P(1)	P(2)
0	0	0	.891	.993	.999
0	1	1	.944	.999	.999
0	2	2	.950	.999	.999
0	3	3	.950	.999	.999
0	4	4	.950	.999	.999
1	0	1	.931	.996	.999
1	1	2	.987	.999	.999
1	2	3	.993	.999	.999
1	3	4	.993	.999	.999
1	4	5	.993	.999	.999
2	0	2	.938	.996	.999
2	1	3	.994	.999	.999
2	2	4	.999	.999	.999
2	3	5	.999	.999	.999
2	4	6	.999	.999	.999
3	0	3	.938	.996	.999
3	1	4	.994	.999	.999
3	2	5	.999	.999	.999
3	3	6	.999	.999	.999
3	4	7	.999	.999	.999

0	2	2	.723	.998	.999
0	3	3	.727	.999	.999
0	4	4	.727	.999	.999
0	5	5	.728	.999	.999
0	6	6	.728	.999	.999
0	7	7	.728	.999	.999
1	0	1	.485	.910	.997
1	1	2	.864	.991	.999
1	2	3	.957	.999	.999
1	3	4	.963	.999	.999
1	4	5	.963	.999	.999
1	5	6	.964	.999	.999
1	6	7	.964	.999	.999
1	7	8	.964	.999	.999
2	0	2	.498	.921	.999
2	1	3	.888	.994	.999
2	2	4	.984	.999	.999
2	3	5	.990	.999	.999
2	4	6	.990	.999	.999
2	5	7	.991	.999	.999
2	6	8	.991	.999	.999
2	7	9	.991	.999	.999
3	0	3	.502	.925	.999
3	1	4	.895	.995	.999
3	2	5	.992	.999	.999
3	3	6	.998	.999	.999
3	4	7	.998	.999	.999
3	5	8	.999	.999	.999
3	6	9	.999	.999	.999
3	7	10	.999	.999	.999
4	0	4	.503	.925	.999
4	1	5	.896	.995	.999
4	2	6	.993	.999	.999
4	3	7	.999	.999	.999
4	4	8	.999	.999	.999
4	5	9	.999	.999	.999
4	6	10	.999	.999	.999
4	7	11	.999	.999	.999

1	0	1	.596	.916	.990
1	1	2	.878	.988	.999
1	2	3	.944	.995	.999
1	3	4	.954	.998	.999
1	4	5	.958	.999	.999
1	5	6	.959	.999	.999
1	6	7	.959	.999	.999
1	7	8	.959	.999	.999
1	8	9	.959	.999	.999
2	0	2	.616	.927	.992
2	1	3	.909	.991	.999
2	2	4	.976	.996	.999
2	3	5	.987	.999	.999
2	4	6	.991	.999	.999
2	5	7	.992	.999	.999
2	6	8	.992	.999	.999
2	7	9	.992	.999	.999
2	8	10	.992	.999	.999
3	0	3	.620	.928	.993
3	1	4	.914	.992	.999
3	2	5	.982	.996	.999
3	3	6	.993	.999	.999
3	4	7	.997	.999	.999
3	5	8	.998	.999	.999
3	6	9	.998	.999	.999
3	7	10	.998	.999	.999
3	8	11	.998	.999	.999
4	0	4	.621	.932	.997
4	1	5	.916	.996	.999
4	2	6	.984	.999	.999
4	3	7	.995	.999	.999
4	4	8	.999	.999	.999
4	5	9	.999	.999	.999
4	6	10	.999	.999	.999
4	7	11	.999	.999	.999
4	8	12	.999	.999	.999
5	0	5	.621	.932	.997
5	1	6	.916	.996	.999
5	2	7	.984	.999	.999
5	3	8	.995	.999	.999
5	4	9	.999	.999	.999
5	5	10	.999	.999	.999
5	6	11	.999	.999	.999
5	7	12	.999	.999	.999
5	8	13	.999	.999	.999

Foldout #2

Table D-8.